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The FireBGCv2 Landscape Fire Succession Model:

A Research Simulation Platform for Exploring Fire and Vegetation Dynamics

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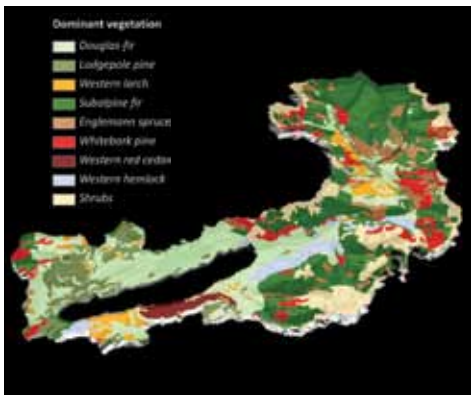

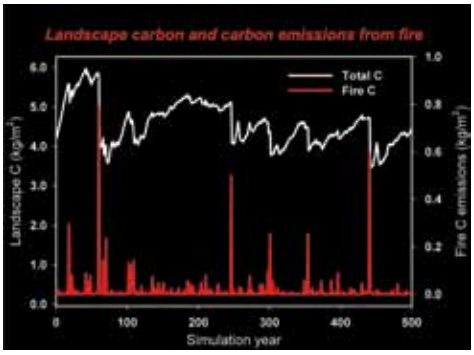

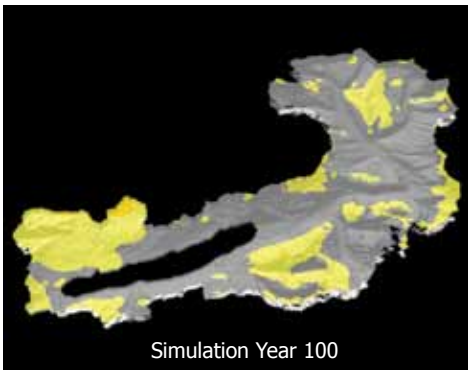
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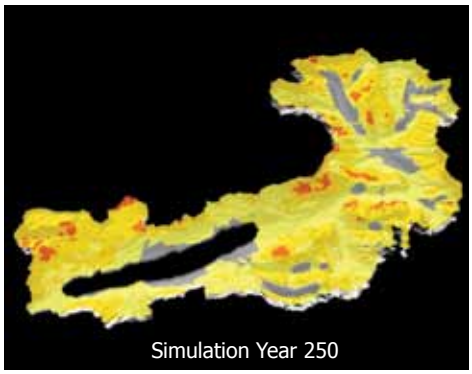
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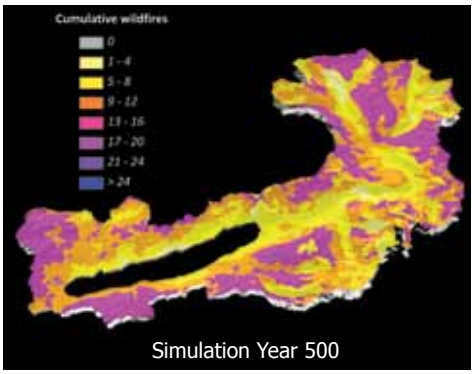

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Abstract

Fire management faces important emergent issues in the coming years such as climate change, fire exclusion impacts, and wildland-urban development, so new, innovative means are needed to address these challenges. Field studies, while preferable and reliable, will be problematic because of the large time and space scales involved. Therefore, landscape simulation modeling will have more of a role in wildland fire management as field studies become untenable. This report details the design and algorithms of a complex, spatially explicit landscape fire and vegetation model called FireBGCv2. FireBGCv2 is a C++ computer program that incorporates several types of stand dynamics models into a landscape simulation platform. FireBGCv2 is intended as a research tool. Descriptions of FireBGCv2 code, sample input files, and sample output are included in this report, but this report is not intended as a user's manual because the inherent complexity and wide scope of FireBGCv2 makes it unwieldy and difficult to use without extensive training. The primary purpose of this report is to document FireBGCv2 in adequate detail to interpret simulation results.

Keywords: spatially explicit, simulation, mechanistic, multi-scale, gap model, climate change, process modeling

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Research Summary

Fire management will face many complex and novel issues in this coming century, including dealing with decades of fuel accumulation from past fire exclusion policies, protecting the expanding wildland-urban interface, and managing fire in landscapes that are being invaded by exotic plants and diseases—all in the face of possible warmer and drier climates. Land managers need innovative tools and information to describe the impacts of past and future human activities on ecosystem dynamics so that they can plan for and respond to the burgeoning issues related to land management and conservation. Field studies, while preferable and reliable, will be problematic to implement because of the large time and space scales involved. Therefore, landscape simulation modeling will play a more substantial role in wildland fire management as field studies become untenable and the pressing issues become more complex.

This report details the design and algorithms of a complex, spatially explicit landscape fire and vegetation model called FireBGCv2. FireBGCv2 is a C++ computer program that incorporates several types of stand dynamics models into a spatially explicit landscape simulation platform. FireBGCv2 is intended as a research tool, but it can be employed in various land management applications providing sufficient expertise exists to parameterize and initialize the model. This report is divided into four parts. In the first section, the FireBGCv2 program is presented in detail with description of most algorithms and protocols. The next section describes how the model is initialized and parameterized and how the results can be interpreted. The third section demonstrates FireBGCv2 by showing output, including maps, graphs, and charts, for two contrasting simulation scenarios—fire regimes under *current* and *future* climate for a landscape in Glacier National Park, Montana, USA. The last section details the strengths and limitations of FireBGCv2. The FireBGCv2 code, sample input files, and sample output from this demonstration are available upon request. This report is not intended as a user's manual because the inherent complexity in FireBGCv2 makes it unwieldy and difficult to use without extensive training and experience in geographical analysis, simulation modeling, and data management.

Contents

Introduction

Fire management will face many complex and novel issues in this coming century. Past fire exclusion policies combined with a successful fire suppression program in the western United States and Canada over the last several decades has resulted in high accumulations of surface and canopy fuels that have increased the potential for severe fires in many ecosystems (Ferry and others 1995, Kolb and others 1998, Keane and others 2002b). Residential expansion into the wildlands increasingly places human populations within fire-prone areas, further escalating the wildfire-caused risk to life and property (Radeloff and others 2005, Berry and others 2006). Rapid climate change over the next several decades may compound the potential for uncharacteristically severe wildfires and increase fire hazard because current projections indicate that future fire seasons may be longer, warmer, and drier (Flannigan and van Wagner 1991, Lenihan and others 1998, Bachelet and others 2000). Emerging climates may also accelerate fuel accumulation and alter vegetation such that future landscapes will experience larger and more intense fires (Keane and others 1996a, Bachelet and others 2001). To complicate matters, invasions of exotic plants and diseases are creating novel fuelbeds that also alter fire regimes and burn severities (Whisenant 1990, Billings 1992). Land management agencies have initiated extensive fuel treatment and ecosystem restoration activities to reduce the possibility of severe wildfires that could damage ecosystems, destroy property, and take human life (Laverty and Williams 2000, GAO 2007). But land managers need tools and information to describe the impacts of future climates and management strategies on ecosystem dynamics (Keane and Finney 2003).

The study of today's landscapes and the complex ecosystems that comprise them is increasingly difficult because of the extensive interactions among vegetation, disturbance, climate, and many other biophysical factors that act across multiple scales of time and space (Starfield and Chapin 1996). Field studies that explore landscape and ecosystem dynamics are becoming problematic because of the large space and time scales that are involved in such interactions. Exploring changes in fire regimes that are caused by mountain pine beetles, for example, might require sampling across large regions for many years or centuries in ecosystems with long fire return intervals (Jenkins and others 2008). Simulation modeling is rapidly becoming indispensible in wildland fire research and management because it synthesizes field study results into a platform that can expand time and space scales to investigate complex landscape and ecosystem feedbacks and relationships (Lauenroth and others 1993, Gardner and others 1999). Recent advances in computer software and hardware technology coupled with development of Geographic Information Systems (GIS), spatial statistics, and new field methodologies have facilitated the creation of complex, mechanistic, spatially explicit landscape simulation models (Keane and Finney 2003, Keane and others 2010). These models can be employed to study the consequences of the interactions of changing climates, fire management, urban development, and disturbance dynamics on landscape ecosystem dynamics.

Simulation modeling will be one of the most important tools for fire research and management because it offers an effective and objective context within which to explore and evaluate management actions and ecological change. Models can be used to simulate effects of potential alternative treatments in order to determine the most effective fuel reduction or ecosystem restoration strategy. Novel treatments can be simulated to determine resultant short- and long-term effects on a diverse array of ecosystem elements. Fire hazard and risk can be simulated to prioritize areas for treatment and to design the most effective treatment prescriptions (Keane and others 2010). Simulation will also be essential to approximate

historical or future landscape conditions that can then be used as reference for ecologically based landscape prioritization and planning (Wimberly and others 2000, Keane and others 2009). Predictive landscape models can also update broad-scale digital maps and inform future sampling strategies for assessing change. The inherent design of simulation models can be used to identify areas of possible research and to prioritize possible research directions. Most importantly, mechanistic landscape simulation models can be used to explore fire, climate, and vegetation interactions; quantify spatial and temporal dynamics of fire regimes; and describe potential fire dynamics under future climates and land management strategies to provide critical information that can help fire managers mitigate potential adverse effects.

This report details the design and algorithms of a complex, spatially explicit landscape fire and vegetation model called FireBGCv2. FireBGCv2 is a C++ computer program that incorporates several types of stand dynamics models into a landscape simulation platform. FireBGCv2 is intended as a research tool, but it can be employed in various land management applications, providing sufficient expertise exists to parameterize and initialize the model. This report is divided into several parts. The FireBGCv2 program is presented first, complete with a detailed description of most algorithms and protocols. Extensive references are provided for algorithms that are not presented. Execution of the model is then described, including initialization, calibration, and parameterization. The third section demonstrates various types of FireBGCv2 output including maps, graphs, and charts that describe and contrast two simulation scenarios–fire regimes under *current* and *future* climate. The discussion section details the strengths and limitations of FireBGCv2. Execution commands are described in the next section, followed by a listing of all FireBGCv2 input files. The FireBGCv2 code, sample input files, and sample output from the demonstration are also included. This report is not intended as a user's manual because the inherent complexity of the FireBGCv2 simulation platform makes it unwieldy and difficult to use without extensive training and experience in geographical spatial analysis, ecological and simulation modeling, and data management. The primary purpose of this report is to document FireBGCv2 in enough detail for proper interpretation of simulation results.

Model Design

Background

History

FireBGCv2 is the second version of the original *FIRE-BGC* model (Keane and others 1995, 1996b) that was created by merging the gap model *FIRESUM* (Keane and others 1989, Keane and others 1990c) with the "big-leaf" mechanistic, biogeochemical *BIOME-BGC* model (Running and Coughlan 1988, Running and Hunt 1993, Thornton 1998) (Figure 1). FireBGCv2 merges the latest ecophysiological simulations of *BIOME-BGC*, as updated by Thornton (1998), into the *FIRE-BGC* design. *FIRE-BGC* simulated individual tree growth, regeneration, and mortality across a landscape using the mechanistic ecophysiological approach of *BIOME-BGC*, and then simulated the ignition, spread, and effects of wildland fire using the *FARSITE* fire growth model (Finney 1996) coupled with *FIRESUM* algorithms (Keane and others 1989). *FIRESUM* was created from the *SILVA* gap model (Kercher and Axelrod 1984) which was developed from the original gap model *JABOWA* (Botkin and others 1972).

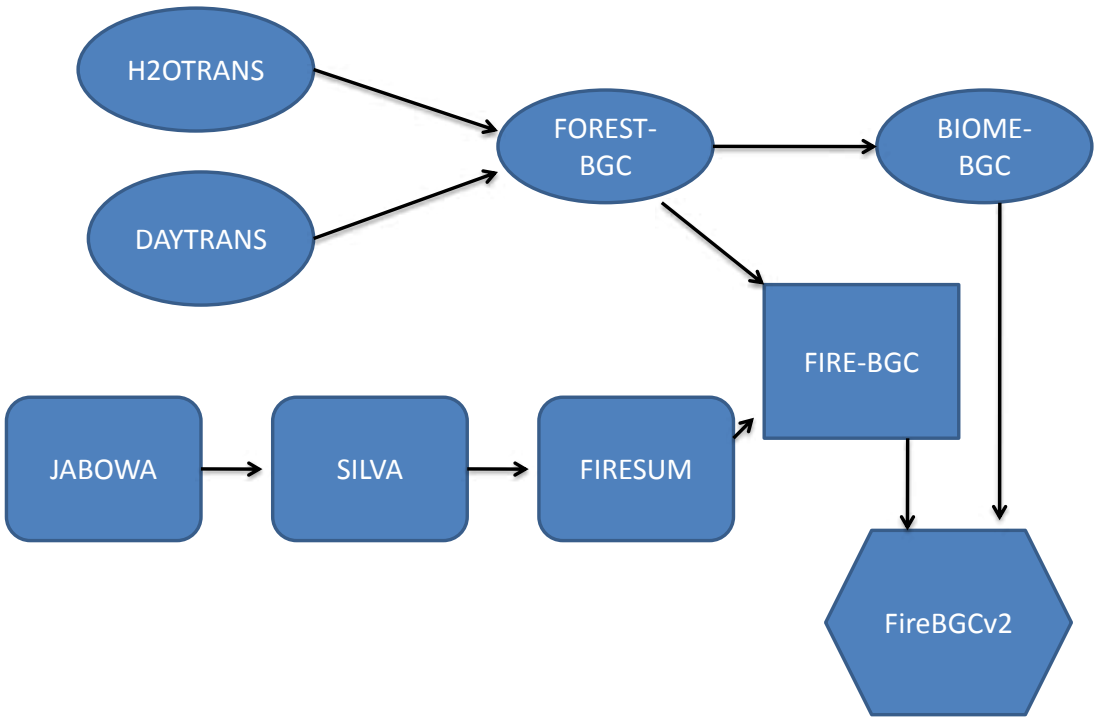

Figure 1. The lineage of the FireBGCv2 model. It is a significant revision of the original FIRE-BGC model (Keane and others 1996) in that it includes many algorithms from BIOME-BGC (Thornton and others 1994). FIRE-BGC was a melding of the FOREST-BGC big-leaf model (Running and Coughlan 1988), which was developed from the Running (1984) models DAYTRANS and H2OTRANS), and the FIRESUM model that was developed by Keane and others (1989) from SILVA (Kercher and Axelrod 1984), which was a variant of the original JABOWA gap model (Botkin and others 1972).

Climate change and fire management scenarios were simulated in *FIRE-BGC* for the McDonald and St. Mary drainages of Glacier National Park to explore possible future landscape composition and structure (Keane and others 1997, Keane and others 1998, Keane and others 1999). However, many computational and design problems with *FIRE-BGC* necessitated a complete revision of the model. For example, *FIRE-BGC* was implemented in a specialized simulation platform called *Loki* that precluded distribution of *FIRE-BGC* code because the *Loki* software was short-lived, unmaintained, and computer platform-specific (Bevins and Andrews 1994, Bevins and others 1995). The *FARSITE* model that was used to spread fires for *FIRE-BGC* simulations had high computational demands, so it could not be executed simultaneously with *FIRE-BGC* to achieve a fully integrated simulation, and *FIRE-BGC* lacked modules needed to comprehensively explore fire management futures and issues, such as prescribed burning, fuel treatment, silvicultural cutting, and wildlife habitat modules. Therefore, a complete redesign was initiated in 1999 to create the new FireBGCv2 model.

FireBGCv2 differs from *FIRE-BGC* in many ways:

- ***One program***. All modules are contained in one program. No external simulation platforms, such as *Loki* for *FIRE-BGC,* are used, meaning the program can be ported to any computer.
- ***Modeling platform***. FireBGCv2 contains many routines that perform the same function in different ways to enable greater modeling flexibility so that simulation comparisons can be made across algorithms and parameter sets. For example, there are three vegetation dynamics modules to explore the influence of model design in succession simulation; FireBGCv2 contains a simple gap model (*FIRESUM*), a mechanistic gap model, and a comprehensive *BIOME-BGC* module.
- ***Management actions***. FireBGCv2 includes a suite of routines that implement prescribed fire and silvicultural cuttings on the landscape based on stand conditions.
- ***Fire simulation modifications***. The fire spread algorithm has been changed to a cell percolation model to speed up execution times. This has resulted in major changes on how fire behavior and effects are calculated. The First Order Fire Effects Model (*FOFEM*) (Reinhardt and others 1997) has also been added to improve the quantitative estimation of fire effects on ecosystem elements.
- ***Wildlife habitat analysis***. A wildlife suitability model has been added to assess the relative value of a stand's cover type and structural stage to any number of wildlife species.
- ***Mountain pine beetle and blister rust***. Along with the detailed simulation of wildland fire, FireBGCv2 also simulates the initiation, spread, and effects of mountain pine beetle and white pine blister rust epidemics.
- ***Tree regeneration improvements***. The regeneration factors of serotiny and sprouting were added at the species level. The regeneration module was also updated to include the influence of weather on reproduction dynamics.
- ***Stream temperature simulation***. There is an empirical module in FireBGCv2 that simulates stream temperature on riparian sites to investigate effects of fire management and climate change on stream temperature and to investigate its implications for fish habitat.

New modules are also being added, such as grazing, weather variability, and fire hazard and risk evaluation, but they are not discussed in this report because they are not fully implemented.

FireBGCv2 was originally developed for the CLIMET project to explore the effects of climate change on fire regimes, vegetation migration, and landscape structure (McKenzie 1998). But, because the renovation of FireBGCv2 took nearly a decade, its scope was expanded to explore many other ecological interactions, so additional modules were integrated into FireBGCv2 to facilitate the

investigation of the effects of climate change on other ecosystem properties, such as stream temperature, carbon, and mountain pine beetles. The model presented here is a snapshot of a fluid landscape simulation tool.

Terminology

The design and structure of FireBGCv2 is complex and, as a result, this report requires a somewhat unique terminology to clearly describe the intricate details of the simulation modules. While this report uses commonly accepted landscape ecology, simulation modeling, and ecosystem science terms, it also includes modified or new terminology to more adequately explain the complexity in the FireBGCv2 design. Since general modeling terminology is especially perplexing, it is important to define those terms.

The first term, *model parameterization,* is the quantification of the major parameters required as input to the model. *Parameters* are static variables, such as smoke emission factors or duff bulk density, which are estimated by the user or model author, and their values remain static throughout the simulation. Input parameters for some models can be *emergent properties* (dynamically simulated output) or output variables from other models. Fire return interval, for example, is an input parameter in *LANDSUM* (Keane and others 2006), but it is an explicitly simulated output variable in *FIRESCAPE* (Cary 1997). *Model initialization* is the quantification of the state variables in a model to begin model execution. *State variables* are those that are explicitly simulated by a model, such as tree carbon, stand nitrogen, or fuelbed loading. *LANDIS*, for example, represents tree dynamics using diameter-species cohorts of tree densities as the state variables (Mladenoff and others 1996). Most state variables are quantified from plot data, GIS maps, and previous simulation results. *Model execution* refers to actually running the model to create outputs to analyze. A model *component* is the abstract representation of a simulated process or characteristic used for descriptive purposes: whereas a *module* is the quantification and representation of that process into a computer algorithm. Model *compartments* are the state variables that represent characteristics or properties of an ecosystem, such as leaf carbon or soil nitrogen (Swartzman 1979). *Processes* are the vectors that affect the dynamic exchange of energy and mass across the landscape, such as photosynthesis and respiration (Forman and Godron 1986). *Mechanisms* refer to the underlying biophysical factors, such as temperature and radiation, that influence the flow of energy across model components.

Many types of variables are incorporated into a simulation model's design (Swartzman 1979). *Intermediate variables* are temporarily computed in the model to be used as input to other equations, algorithms, and decision thresholds and also as output for the user to interpret the results. *Flux variables* represent vectors that move energy, water, and carbon across model state variables. The output contains predictions or estimations of *response variables*, which, in this paper, are directly needed to fulfill the study or project objective. *Explanatory variables* are output from the model that explains model behavior.

There are many types of simulation models and many types of modules that are included within simulation models. They are usually categorized into four approaches: empirical, deterministic, stochastic, and mechanistic (Table 1). *Empirical models* are primarily built on statistical relationships that are derived from actual data. *Deterministic models* use generalized functions to represent the relationships that drive simulation dynamics. *Stochastic models* use probability distributions to represent primary ecosystem processes. *Mechanistic models* attempt to use fundamental biological and physical relationships to simulate the underlying processes or causal mechanisms that dictate system behavior. While all of these model approaches have various advantages and disadvantages (Table 1), the best simulation models and modules are often combinations of all four types.

Table 1. Advantages and disadvantages of the four approaches used in simulation modeling.

Attribute	Empirical	Deterministic	Stochastic	Mechanistic
Complexity	Low	Low	Moderate	High
Parameter requirements	Low	Moderate	Moderate	High
Accuracy	High	Variable	Low	Variable
Exploratory uses	Low	Moderate	Moderate	High
Management application	High	High	Low	Moderate
Portability to other situations	Low	Moderate	Moderate	High
Expand-ability	Low	Moderate	Moderate	High
Required Expertise	Low	Moderate	Moderate	High
Computer requirements	Low	Moderate	Moderate	High
Preparation time	Low	Low	Moderate	High

Landscape structural and compositional terms can also be confusing. The spatial and size distribution of patches describes *landscape structure*, while *landscape composition* is often described by the relative abundance of ecosystem features across the spatial domain (percent area by cover types, for example). A *stand* is often referred to as an area of homogeneous vegetation, but in this report, stand also represents an inherent scale within the model. *Polygons* often refer to stands that are digitally mapped. The term *patches* is synonymous with stands or polygons in this paper. Ecosystem features, such as the dominant plant species (cover type) or vertical stand structure (structural stage), and disturbance properties, such as fuel models and fire regime, can be related to each polygon. Several terms are used to describe spatial data. A *data layer* is a digital map that describes a particular attribute. Data layers can be raster or vector. *Raster layers* are comprised of a grid of square pixels that represent the mapped area, and each pixel has a resolution (size) and is assigned an attribute. *Vector layers* are represented by lines that represent polygon boundaries. FireBGCv2 only uses ASCII raster data for inputs and outputs both in maps and input files. In this report, the terms *data layer, raster layer*, and *digital map* are used synonymously.

There are several ecological terms that need further description. In FireBGCv2, the term *undergrowth* describes all the non-tree species that can inhabit a stand. The *understory* is composed of trees in the lower canopy stratum, and *overstory* is comprised of trees in the highest canopy stratum. *Fuel*, in this report, is the biomass of dead and live organic material in the unique classes or categories that are required by the fire behavior models. The fuelbed is synthesized from various state variables at the different organizational scales.

Report Conventions

This report uses many unique conventions and symbologies to describe the internal workings of the FireBGCv2 model. First, most variable names are in upper case (RNUM, for example) and they are defined in the text and in an index at the end of this report. However, a special class of variables has a lower-cased letter that starts the variable name, such as rTREE. Variables that have the lower-cased "r" as the first letter are called "reduction" variables or scalars, which are commonly used in ecological gap modeling (Botkin 1993). In many gap models, simulated processes are often scaled from 0.0 to 1.0 to reflect their effect on state variables. In FireBGCv2, reduction variables are multiplied by a state or flux variable to scale effects and simulate interactions. For example, rTREE is a reduction variable that represents the influence of the number of seed trees on seed dispersal; it is scaled from 0.0 to 1.0 (0.0 for no seed-producing trees and 1.0 for greater than five seed-producing trees per hectare).

Variables with lower-cased letters in the middle of their names are often major state variables that represent important carbon, nitrogen, or water pools.

For example, LeafC is the leaf carbon pool of a stand or tree, and AvailN is the available nitrogen pool. Variables with all capital letters are usually intermediate variables or input parameters, while variables with lower-cased letters within the name are state variables.

The units throughout the report follow SI but some have special coding, especially the mass units. It is difficult to keep track of the origin of the mass of certain state and flux variables. State variables that have mass, for example, have the unit of kg, but it is unknown what that mass represents–it could be kg of carbon or kg of biomass. Therefore, we have placed a capital letter after the kg mass unit that indicates the origin of that biomass:

- kgW signifies kg of water for all water fluxes and state variables,
- kgC is kg of carbon,
- kgB is kg of biomass, and
- kgN is kg of nitrogen.

All files in this report have a unique suffix where ".in" is used for input files and ".out" is used for output files. All input file names are specified by the user, so they can have any name. We refer to them as "Filename.suffix" to simplify discussion, where the Filename is an informative name for a file and the suffix represents its use. For example, simulation parameters are input to the simulation in an ASCII file, which we have named "Sim.in," where Sim refers to the "Simulation parameters" and .in refers to the fact that this is an "input file." Throughout this report, we have used the file name to reference where the input variable is specified by the user. For example, a species' specific leaf area (SLA) is specified by the user in the Species.in file. The content and structure of all files are detailed in the "Input File Structure" section.

All models or important modules are listed in italics and capital letters, such as *FOREST-BGC,* except for FireBGCv2. The variable names used in this report are not the same variable names used in the FireBGCv2 program because C++ program variable names are often long, connected with a pointer that references the scale, and redundant across program modules. Therefore, it would be difficult to debug the FireBGCv2 program using the variable names in this report; instead use the extensive documentation that is embedded in the code.

Model Description

FireBGCv2 is best described as a mechanistic, individual-tree, gap model that is implemented in a spatial domain (Keane and others 2004a). The model was developed by integrating empirically derived deterministic functions with stochastically driven algorithms to approximate landscape and ecosystem behavior across time and space. Empirical and deterministic functions are used to represent ecological processes, such as autotrophic respiration, that are heavily studied and to show where the variability of the process is somewhat understood and predictable. Stochastic functions are used to represent ecological processes that are highly variable, somewhat unstudied, and difficult to quantify, such as fire ignition, tree mortality, and snag fall. FireBGCv2 simulates ecological processes across and within scales so that cross scale interactions can be appropriately represented and accounted for in landscape behavior.

From an applications viewpoint, FireBGCv2 is more of a simulation platform than a single, integrated, linear model. Some ecosystem processes are simulated in multiple ways in the model. Fire spread, for example, can be simulated using a cell-automata model or a simplistic spread model. Tree dynamics can be simulated using the *BGC* algorithms, a mechanistic gap model, or a simplistic gap model. Fire behavior can be simulated using the Rothermel spread model (Rothermel 1972) or the Albini *FIREMOD* model (Albini 1976). Therefore, FireBGCv2 often has multiple approaches and redundant modules that enable users to simulate

important ecosystem processes in several ways. This platform structure accommodates explorations in the efficiency and accuracy of modeling approaches and predictions. Moreover, FireBGCv2 includes a number of other previously developed programs, namely *BIOME-BGC*, *FIREMOD* (Albini 1976), and *FOFEM* (Reinhardt and others 1997).

FireBGCv2 simulates landscape dynamics by integrating fundamental ecological processes across multiple spatial and temporal scales (Figure 2). Wildland fire ignition and spread, along with cone crops and seed dispersal, are simulated at the landscape level at the end of the simulation year. Weather and species phenology are simulated at the site level at a daily time step. Most action in a FireBGCv2 simulation occurs at the stand level where the flow of carbon, nitrogen, and water are moved across various components within the model (Figure 3). Litterfall and decomposition dictate forest floor dynamics; rainfall, leaf area, and temperature govern water dynamics; and photosynthesis and respiration dictate carbon dynamics (Figure 4). Tree growth, establishment, and mortality are simulated at the tree level. Disturbance effects, such as fuel consumption, tree mortality, and soil heating, are computed at each scale. All simulated processes have cross scale implications (Figure 2). For example, carbon is fixed by tree leaves (needles) via photosynthesis using solar radiation and precipitation weather inputs, and it is then distributed to leaves, stems, and roots, and accumulated litter, duff, and soil to eventually act as fuel for a fire (Figure 4). These forest floor compartments lose carbon through decomposition. Nitrogen is cycled through the system from the available nitrogen pool.

FireBGCv2 is a cumulative effects model best used to study long-term changes to landscape ecological regimes rather than as a prognostic model to predict the near future. Since FireBGCv2 has many stochastic elements, it shouldn't be used to move landscapes forward or backward in time to determine what will be where and when. Rather, FireBGCv2 is best used to simulate the long-term interactions of disturbance, climate, and vegetation across several model runs to determine trends in landscape behavior and response. Because of this, FireBGCv2 should be run at least five times for time periods that are at least two to five times longer than the longest fire return interval, and results should be summarized to determine relative trends in ecological patterns and processes. And, as with most mechanistic models, the simulation results are best used when compared relatively with other simulation results in a scenario approach to evaluate trends; the absolute values of FireBGCv2 predictions can often be inaccurate, but they are precise, especially if averaged over many simulation replicates.

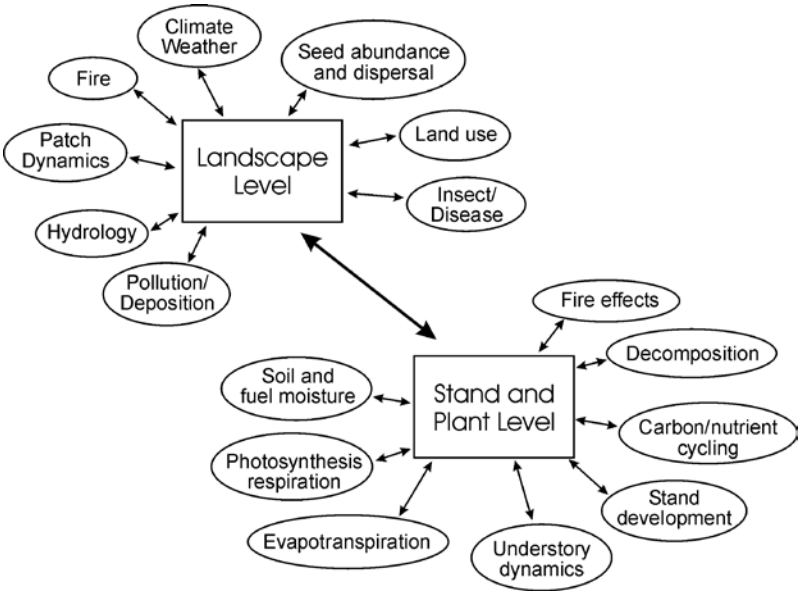

Figure 2. A general description of the ecosystem processes integrated into the FireBGCv2 model at multiple scales of time and space at both the landscape and stand scales.

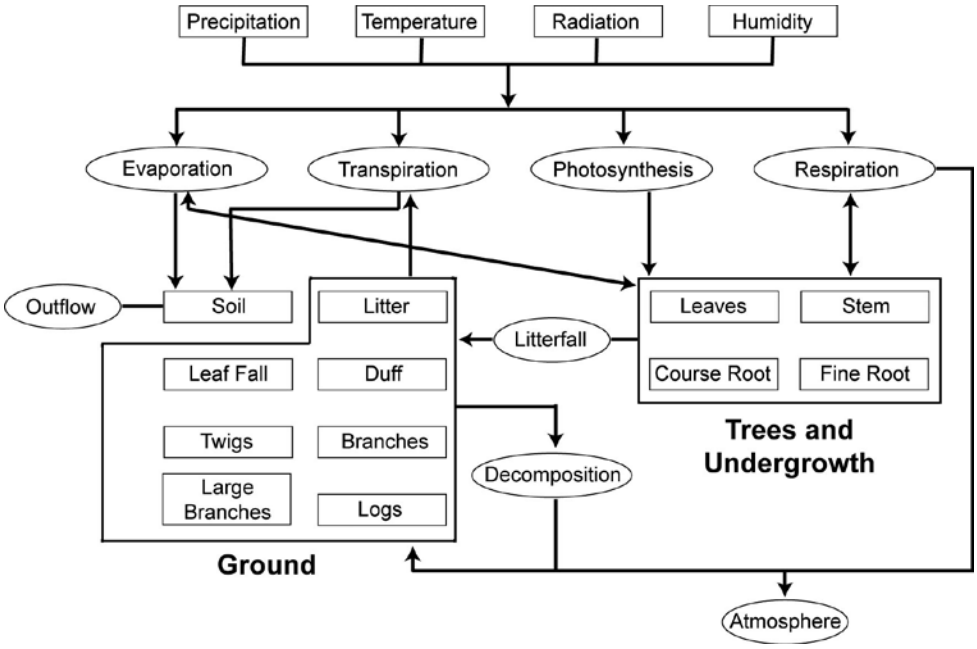

Figure 3. A generalized diagram that illustrates the complexity of ecological processes that are simulated on the landscape. The biomass that is dropped to the ground from the simulated trees and undergrowth is stratified by seven ground components to facilitate the simulation of fire behavior and effects.

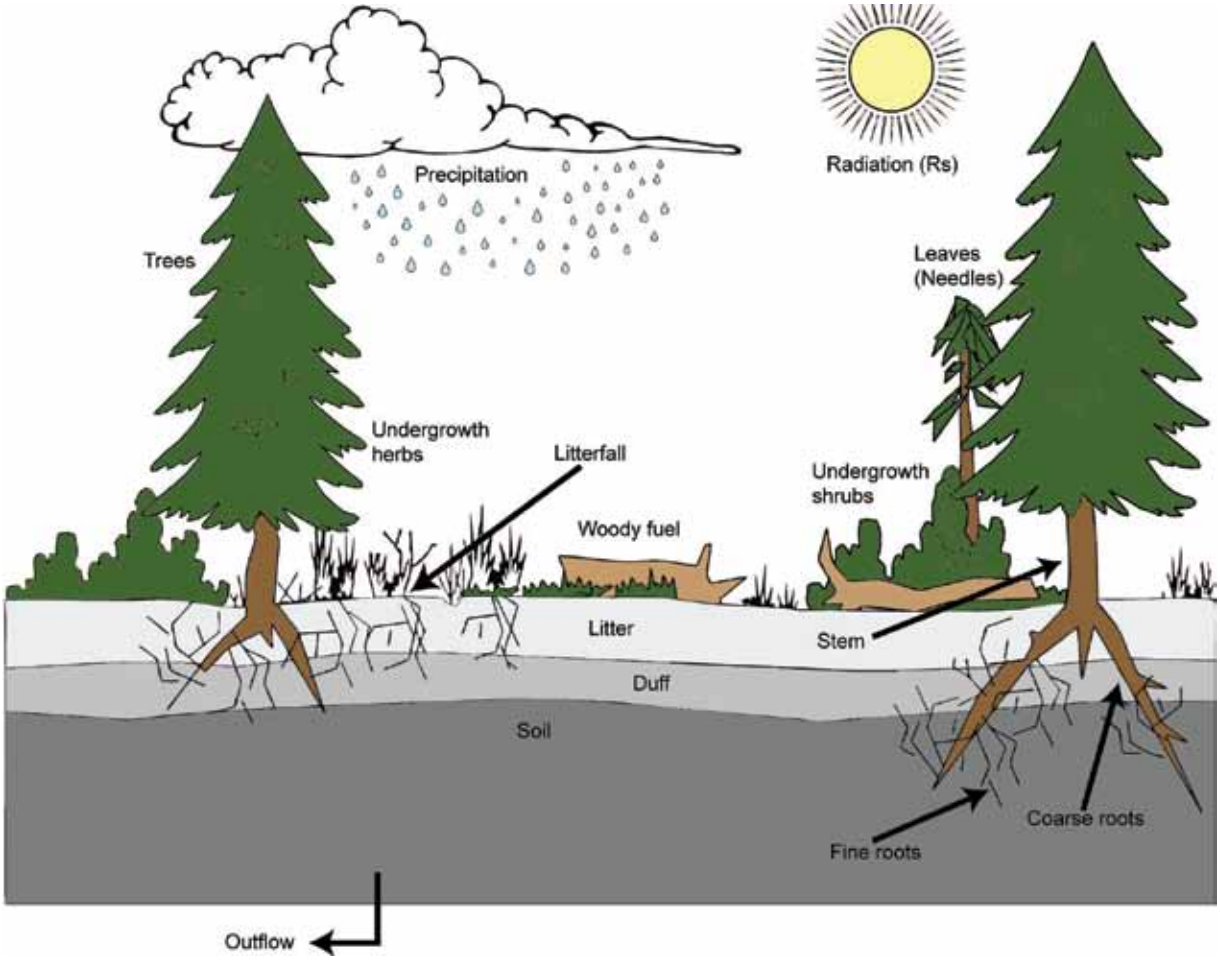

Figure 4. General illustration of the important processes and ecosystem components represented in a FireBGCv2 simulation.

Design and Structure

As mentioned, FireBGCv2 was designed as a research platform to explore climate, fire, and vegetation dynamics across small landscapes. It was also designed to conduct various simulation experiments in modeling science to understand consequences of simulation design, such as investigating appropriate and optimum simulation detail when simulating landscape dynamics. This program was not developed to be used by managers to simulate possible management alternatives, even though it could be used for some management applications, providing sufficient expertise exists to parameterize and initialize the model. Because of this, FireBGCv2 has some major drawbacks for general use:

- **No graphical user interface**. There is not a slick, user-friendly interface to facilitate execution, parameterization, and initialization. All inputs are in ASCII files that are edited with a standard text editor and are read directly by the program.
- **No standardized output**. FireBGCv2 was built to be flexible in the output generated by the model, especially in time and space. As a result, there is no general set of outputs that are created by the model. The user must design the output files to fit the simulation objective.
- **No version control**. FireBGCv2 was designed so that code could be modified by the user to accommodate the simulation of a new ecosystem element, process, or characteristic. As a result, the FireBGCv2 versions are highly fluid and dynamic, and there is no organization and maintenance of code updates and version control. However, we will manage FireBGCv2 versions by posting the most recent version at the www.firelab.org website.
- **No maintenance**. There is no organization or person who manages FireBGCv2 code across multiple users. The latest versions will be posted to www.firelab.org, but there will be no formal maintenance plan associated with posting.

The model description and code in this report represent one version in a long line of updates made to FireBGCv2 to facilitate new modeling projects. We anticipate more modifications to the code in the future with each novel application of FireBGCv2.

Organizational Scales

There are five inherent scales built into FireBGCv2 design that correspond to spatial domains or organizational layers represented within the model (Figure 5). The first is the *landscape* scale, which is the spatial context for all processes and characteristics that occur in the simulation. It is usually defined as a large expanse of land (greater than 10,000 ha) that is delineated by the natural boundaries that control the major properties of that ecosystem, such as climate, vegetation, hydrology, and disturbance. The landscape is divided into biophysical units of land called *sites* that have similar topography, soils, weather, and potential vegetation. The model keeps the spatial boundaries of sites static within the landscape throughout FireBGCv2 simulations. Nested within each site is another scale called *stands.* That is, each site is comprised of a number of stands that can be differentiated by vegetation composition and structure. Each stand is assumed to be comprised of pixels with homogeneous vegetation and disturbance conditions. By definition, stand boundaries cannot extend past site boundaries. Stand boundaries are not stationary in FireBGCv2. Instead, simulated succession, fire, insects, and pathogens serve to alter stand boundaries within a site. Stand boundaries almost always change after major disturbances. Because of computational limitations, FireBGCv2 does not explicitly model all entities across the entire spatial extent of a stand. Instead, the model simulates ecosystem processes in a small representative portion of the stand called the *simulation plot*. The size and characteristics

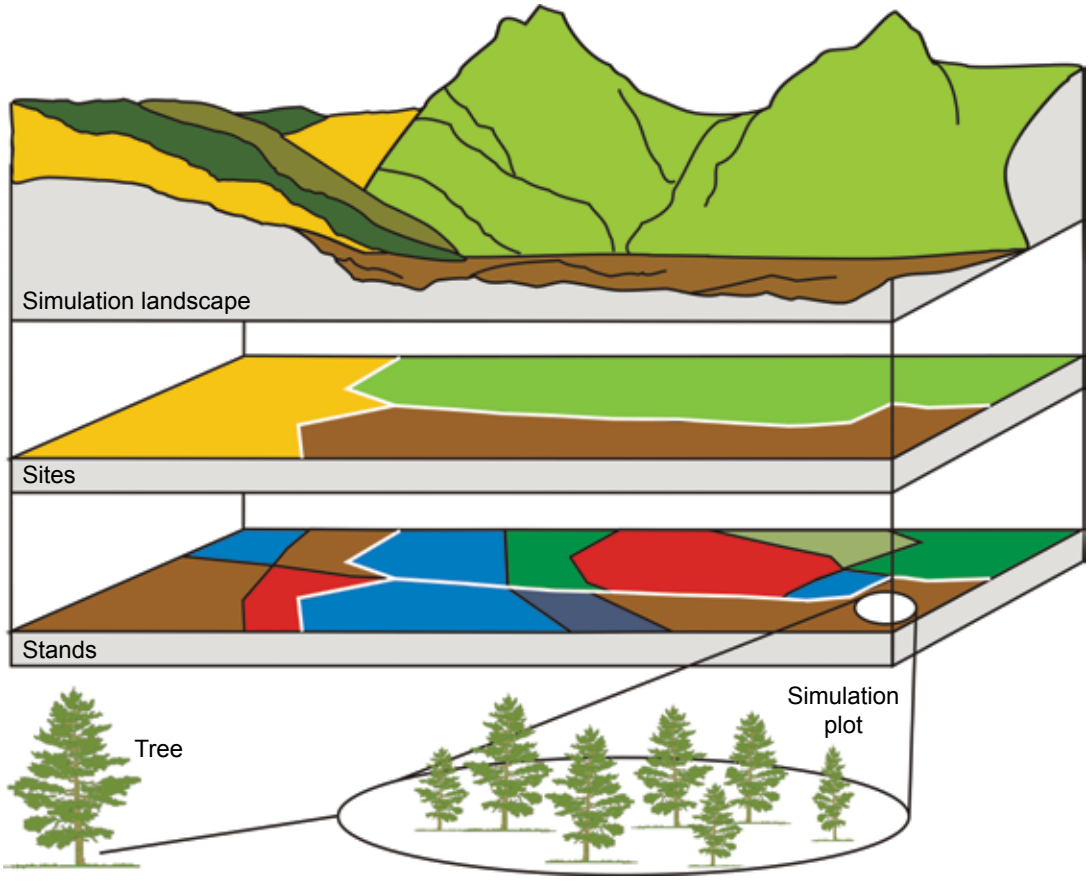

Figure 5. The five organizational scales built into the design of FireBGCv2: landscape, site, stand, species, and tree.

of the simulation plot are input to FireBGCv2 and can be adjusted to improve computation time and to better simulate ecological processes. Conditions within the simulation plot are assumed to be representative of the entire stand**.**

The fourth organizational scale is the *species* level. Any number of species can inhabit a stand and many modeled processes, such as cone production and phenology, are performed at the species level. The fifth and finest level of organization is the *tree* level. Each tree within a simulation plot is explicitly modeled in the FireBGCv2 architecture. Many structural and ecophysiological attributes of each tree, such as leaf carbon, diameter, and height, are simulated in FireBGCv2. Discussion of FireBGCv2 simulation methods is stratified by these organizational levels in this report.

FireBGCv2 links many cross-scale interactions in the simulation of ecosystem processes. The treatment of weather in the model is a good example of linkages that progress downward in organizational scale. The weather year is selected for the entire landscape and then used to access weather for a site. Each site is assigned a separate daily weather file. Photosynthesis and respiration are computed from the daily weather data at the stand level for that site. Important weather events such as frost and drought are computed at the stand level for the simulation of species dynamics, such as regeneration. Carbon that is fixed through photosynthesis at the stand level is allocated to the trees based on the distribution of radiation in forest canopy, which is computed from the site weather file and the stand's canopy structure. FireBGCv2 also accounts for interactions that occur upward in organizational scale. At the end of the simulation year, FIREBGCv2 sums all carbon and nitrogen tree compartments for a new estimate of stand carbon and nitrogen components. Simulated fires burn a stand's forest floor compartments (fuels) but use site-level weather and topography for computation of fire spread and intensity at the stand level.

Major Design Assumptions

In the previous version of FireBGCv2 (*FIRE-BGC*), the melding of the *BGC* models with a gap model created some undesirable behavior and odd side-effects in simulation results. *BIOME-BGC* and *FOREST-BGC* are equilibrium models that simulate ecological processes and their interactions with climate to describe changes in ecosystem properties that are explicitly represented in the model by carbon, water, and nitrogen pools. The problem with using *BGC* models to represent tree and undergrowth dynamics is that most ecosystem elements, such as trees, fuels, and grasses, are rarely in equilibrium but rather are always experiencing perturbations from a diverse number of agents, such as fire, disease, and insects. These perturbations constantly and abruptly change carbon, nitrogen, and water pools over short time periods. The *BGC* equilibrium model cannot respond to these instantaneous perturbations to produce realistic carbon, nitrogen, and water fluxes because the model state variables must first come into equilibrium with the climate. As a result, there was often a lag in *FIRE-BGC* carbon, water, and nitrogen flows to tree growth after major changes to stand-level carbon pools brought about by disturbance that caused unrealistic tree diameter and height growth patterns (Keane and others 1996b). To remedy this, we removed the intimate link between tree and stand carbon that was present in *FIRE-BGC,* and instead, stand-level carbon and nitrogen pools are recalculated each year based on empirically derived carbon estimates at the tree, ground, and undergrowth levels. These updated carbon pools are then passed to the *BGC* routines to mechanistically compute the ecological processes that govern the fluxes of carbon, water, and nitrogen. So, FireBGCv2 is missing the seamless, comprehensive, and complete linkages between stand and tree biogeochemical processes and now uses the list of trees, undergrowth, and ground components as the critical state variables instead of carbon, water, and nitrogen state variables. We feel this loss in ecological process interaction is more than balanced by the gain in consistency, accuracy, and model robustness.

Another design change from *FIRE-BGC* to FireBGCv2 is the simulation of the nitrogen pools. The *BGC* simulation of vegetation dynamics still simulates changes in nitrogen pools, but now, all changes in nitrogen pools are calculated from changes in the carbon pools, and nitrogen pools are updated at the beginning of a simulation year. So, for example, instead of having a dynamic, independent nitrogen pool for foliar nitrogen and corresponding nitrogen fluxes, the foliar nitrogen is now calculated from the carbon:nitrogen ratios entered in input files. Only the available nitrogen pool (AvailN) is dynamically modeled across simulation years. The nitrogen pools are only used in a *BGC* simulation, and again, the carbon and nitrogen pools are updated each year.

All parameters and initialization data are input into the FireBGCv2 program using ASCII files, and all simulated outputs are printed to ASCII files. These files are specified by name in a metafile called the Driver.in file. All input files have the .in suffix and will be presented by name in the following sections. Their format and structure is presented in the "Input File Structure" section. All output files have a fixed column format with each column containing a value of a user-selected variable output at a user-specified time interval. Output files have an .out suffix. The following sections will refer to various parameters and the files in which they are specified.

Module Design

This section presents the major state variables and parameters that are simulated or referenced at each organizational scale in the FireBGCv2 model (Figure 5). This is not an exhaustive list of state variables: these are the most important state variables needed to understand model dynamics and algorithms.

Landscape Simulation

The landscape-level state variables are: (1) area burned, (2) number of fires, and (3) area in mountain pine beetle host species. These variables are updated yearly and are used in finer scale process simulations. From the burned area, the model computes fire regime information including fire return interval, fire rotation (cycle), and number of fires per year.

Site Simulation

Site state variables are used to simulate ecological processes at finer scales. The dynamic variables that are simulated at the site level include:

- DSS (days). Days since last snowfall.
- DSR (days). Days since last rainfall.
- RUST (flag). Flag indicating the initiation of a rust epidemic.
- BEETLE (flag). Flag indicating the initiation of a beetle epidemic.
- NFREEZDAY (days). Number of days it is freezing for mountain pine beetles (>-30 ^{o}C).
- NFROZDAY (days). Number of days it is colder than freezing for beetles (>-40 ^{o}C).
- $RUST_{rh}$ (%). Average relative humidity in September used for simulating rust dynamics.
- $RUST_{temp}$ (^{o}C). Average temperature in September used for simulating rust dynamics.

The values of these variables are updated each year or day, depending on the algorithm and variable type.

There are a number of site variables that are assigned as parameters in the Site.in file or computed at the start of the simulation and used in various processes throughout the simulation, especially in the phenology simulation. These variables are introduced in the following sections where they are first used. Some important site parameters used throughout the program are:

- LAI_{max} (m^2 m^{-2}). Maximum projected leaf area index for the site.
- BA_{max} (m^2 ha^{-1}). Maximum basal area for the site.
- SI (m). Site index for all tree species for that site.
- SAP_{max} (saplings m^{-2}). Maximum number of saplings (trees greater than 1.37 m tall) that can regenerate in any one year across all species.
- LAG (year). Number of years after a fire before regeneration can occur.
- FRI (year). Fire return interval or number of years between fires for all land area within a site.
- FSIZE (ha). Average fire size.

These are the most important site-level parameters, and they dictate many processes at several scales. Another component that is specified at the site scale is fuel characteristics, which is how fuels are represented in the model.

Fuel Representation

All fuel properties in FireBGCv2, except for loading and moisture, are static input parameters that are specified by the user in the Fuel.in file. Fuels attributes are assigned by live and dead components, which are further stratified by shrub, herbaceous, and four size classes of downed dead woody fuel (twigs, branches, large branches, and logs that correspond to 1, 10, 100, and 1000 hr fuels, respectively) (Figures 4 and 6). Each component has a list of attributes that are used in the calculation of fire intensity and fire effects. Currently, FireBGCv2 recognizes

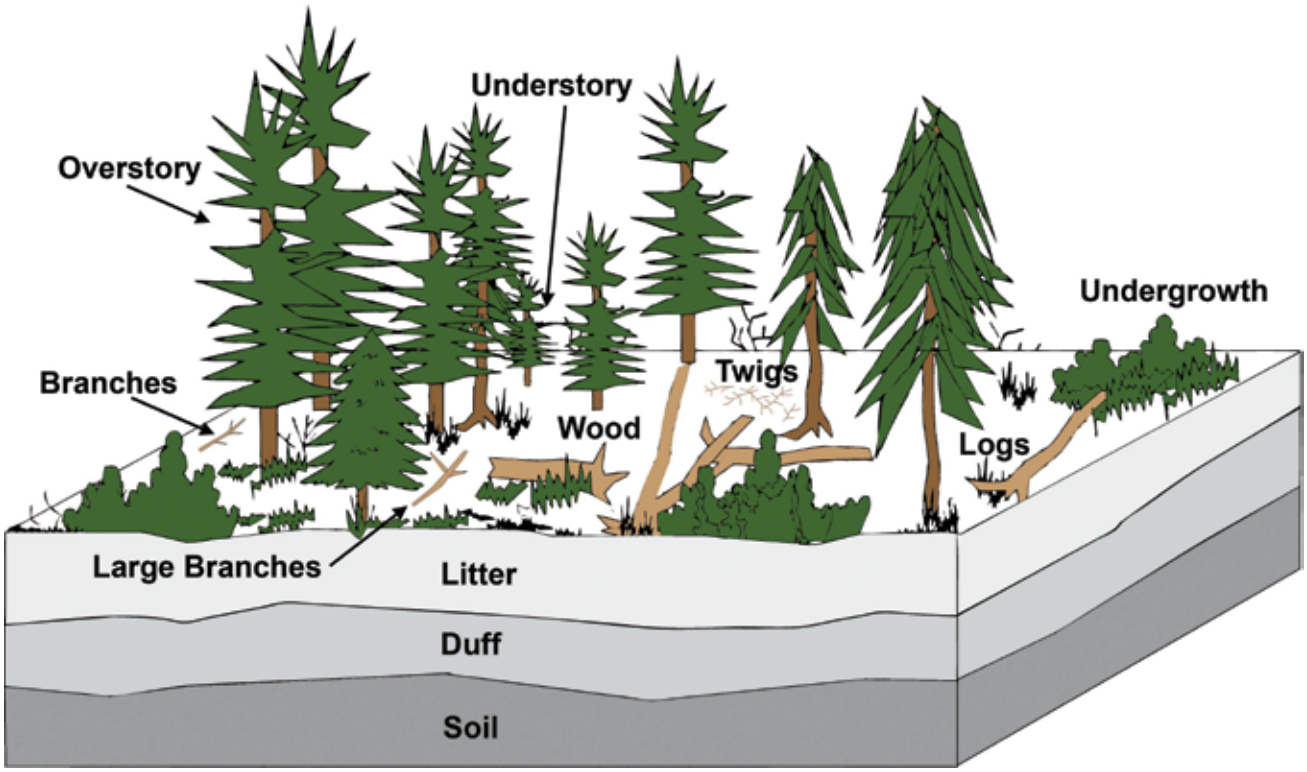

Figure 6. A generalized figure of the important components of a stand that are simulated in FireBGCv2. The undergrowth contains all non-tree species and is represented by a set of guilds or plant functional types. The forest floor includes all wood, litter, and duff, and wood is separated into four size classes based on diameter of the woody particle (twigs, branches, large branches, and logs). The overstory is composed of all trees greater than 10 cm DBH and the remaining small trees are the understory.

a maximum of eight dead and two live fuel components, but these parameters can be easily changed for future applications (Figure 7). Some fuel model parameters are not stratified by fuel component. Values for duff and litter bulk densities (BULK) and surface area to volume ratios (MPS) are taken from Brown (1974, 1981) and are used to calculate duff and litter depth (see "Regeneration" in the "Species Processes" section).

The following parameters are specified in the Fuel.in file for each of the live and dead fuel components:

- RHOP (kg m^{-3}). Fuel particle density.
- LHV (BTUs). Heat content of fuel.
- MPS (m^2 m^{-3}). Surface area to volume ratio.
- MOIST (proportion). Fuel moisture at the time of fire, expressed as a proportion of dry weight.
- CONSUME (proportion). Proportion of fuel that will be consumed in the fire.

Also specified in the Fuel.in file are the moisture of extinction of live and dead fuels (MEXT, proportion), bulk density (kgB m^{-3}) of the duff and litter ground layers ($BULK_d$ and $BULK_l$) and the live and dead fuelbed ($FBULK_l$ and $FBULK_d$), and depth of the fuelbed (FDEPTH, m). The spread component and wind reduction factors are also specified for a fuel model but are not used in the model. These fuel models are specified at the site level.

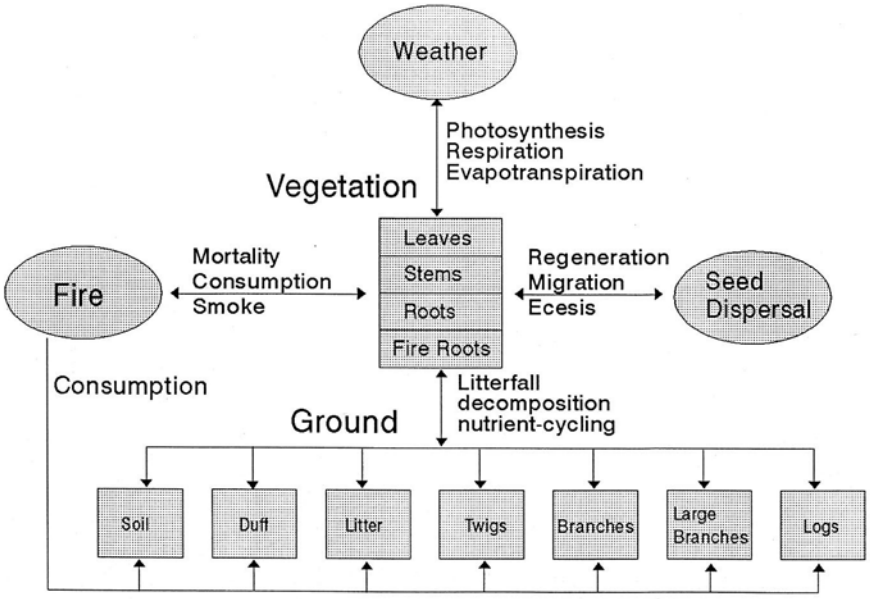

Figure 7. The forest floor components that comprise the fuelbed and the processes that affect the flux of carbon and water to these components.

Stand Simulation

The stand scale is the primary scale of analysis in the FireBGCv2 model, and it is at this scale where most important ecological processes are simulated (Figures 2, 3, and 7). Each stand has two types of state variables: (1) variables that describe general stand dynamics, and (2) variables that describe the dynamics of unique stand compartments.

The important dynamic stand state variables that are critical to the simulation of most other modeled ecological processes are as follows:

- LA (m^2), LAI, PLAI, PLAISUN, PLAISHADE (m^2 m^{-2}). The leaf area (LA), all-sided leaf area index (LAI), projected leaf area index (PLAI), PLAI for only the foliage in the sun, and PLAI for the shade leaves, respectively.
- ALBEDO (proportion). The proportion of the direct radiation that is reflected back into the atmosphere as indirect radiation.
- FRI (year), YSF (year), NFIRES (number). Fire return interval, years since last fire, and the number of fires recorded for this stand during the simulation.
- FBFM (index). Fire behavior fuel model number (Anderson 1982).
- BA (m^2 ha^{-1}). Basal area of stand.
- HT (m). Stand height or average height of all trees in the overstory.
- HBC (m). Height to base of canopy or average height to crown base for all trees in the overstory (>10 cm DBH).
- CAREA (m^2). Canopy area of all trees in the stand.
- CC (%). Percent canopy cover of all trees in the stand.
- PLA_j (m^2), AL_j (index). Projected leaf area and proportion of available light for canopy layer j.
- $SEEDTREE_i$ (trees), $SEEDPROB_i$ (probability), $SPPBA_i$ (m^2 ha^{-1}), $SPPBIOMASS_i$ (kgB m^{-2}). The number of seed producing trees, average relative probability of a seed hitting the stand, basal area, and amount of aboveground biomass by species *i*.
- $HABSUIT_k$ (index). Habitat suitability index for wildlife species *k*.

There are three major stand compartments that are simulated separately from other stand-level processes. Their design is discussed next.

Carbon and Nitrogen Pools

The carbon pool state variables at the stand level are as follows:

- LeafC (kgC). Carbon in leaf biomass.
- $LeafC_{max}$ (kgC). Carbon in leaf biomass at peak of growing season.
- FrootC (kgC). Fine root carbon.
- LivestemC (kgC). Amount of carbon in the live stem, including twigs, branches, and boles.
- DeadstemC (kgC). Amount of carbon in the dead stem, including bark, twigs, branches, and boles.
- LivecrootC (kgC). Amount of carbon in the live coarse roots.
- DeadcrootC (kgC). Amount of carbon in the dead coarse roots.
- PSN (kgC). Amount of carbon fixed as photosynthate during the year for that tree.
- RESP (kgC). Amount of carbon lost to respiration during the year for that tree.
- StemC (kgC). Previous year's stem carbon (live and dead).

Ground Simulation

The forest floor is an important component in FireBGCv2 design because it represents the dynamic properties of the fuelbed that are used to simulate fire (Figure 7). There are eight ground components that are represented as state variables at the stand level. They were designed to accurately represent forest floor processes and to be used directly in the fire behavior models (Table 2):

- LeaffallC (kgC m^{-2}). The total leaf carbon that has fallen on the ground during the simulation year.
- LitterC (kgC m^{-2}). The total leaf carbon in the litter layer, comprised of the remaining LeaffallC after many highly mobile substances have been lost.
- DuffC (kgC m^{-2}). The decomposed organic material from woody and non-woody sources that represents a long-term carbon pool on the soil surface.
- SoilC (kgC m^{-2}). The total sloughed fine root carbon and the carbon that transitions from the duff to the soil.
- W1C (kgC m^{-2}). The carbon in the fallen twigs of trees and shrubs. Twigs are downed woody fuel particles that are 0.0 to 1.0 cm diameter. In fuels terminology, this material is called 1 hour downed dead woody fuel (1 hr), hence its variable name.
- W10C (kgC m^{-2}). The carbon in the fallen branches of trees and shrubs. Branches are downed woody fuel particles that are 1.0 to 3.0 cm diameter. In fuels terminology, this material is called 10 hour downed dead woody fuel (10 hr).
- W100C (kgC m^{-2}). The carbon in the fallen large branches of trees and shrubs. Large branches are downed woody fuel particles that are 3.0 to 7.0 cm diameter. In fuels terminology, this material is called 100 hour downed dead woody fuel (100 hr).
- W1000C (kgC m^{-2}). The carbon in the fallen logs of trees and shrubs, such as snag fall. Logs are downed woody fuel particles that are greater than 7.0 cm diameter. In fuels terminology, this material is called 1000 hour downed dead woody fuel (1000 hr).

These ground components are represented by carbon pools instead of biomass pools so that FireBGCv2 can easily adjust the pools based on *BGC* ecosystem process simulations (Figures 3 and 7).

Table 2. Description of the forest floor compartments. Forest floor fuels are litter (LitterC + LeaffallC), duff, twigs, branches, large branches, and logs (NA means not applicable)

Stand ground compartment	Attributes		
	Name	Particle Size (cm)	Description
LeaffallC	Fresh litterfall	<0.2	Freshly fallen litter less than 1 year old
LitterC	Litterfall	<0.2	Litterfall that has lost highly mobile materials (carbon)
DuffC	Duff	NA	Organic carbon material with indiscernible origins
W1C	Twigs	<0.6	Down, dead woody carbon material, 1 hr fuels
W10C	Branches	0.6 to 2.5	Down, dead woody carbon material, 10 hr fuels
W100C	Large Branches	2.5 to 8.0	Down, dead woody carbon material, 100 hr fuels
W1000C	Logs	>8.0	Down, dead woody carbon material, 1000 hr fuels
SoilC	Soil	NA	Organic carbon found in the mineral soil

Undergrowth Simulation

The most difficult structure to understand in FireBGCv2 design is how the undergrowth (non-tree species) is represented in a simulation (Figure 8). The simulation of the undergrowth involves assigning a "plant model" to each site. Each plant model contains a set of "guilds" that represent suites of functionally similar undergrowth species (shrub and herbaceous plant functional types, for example).

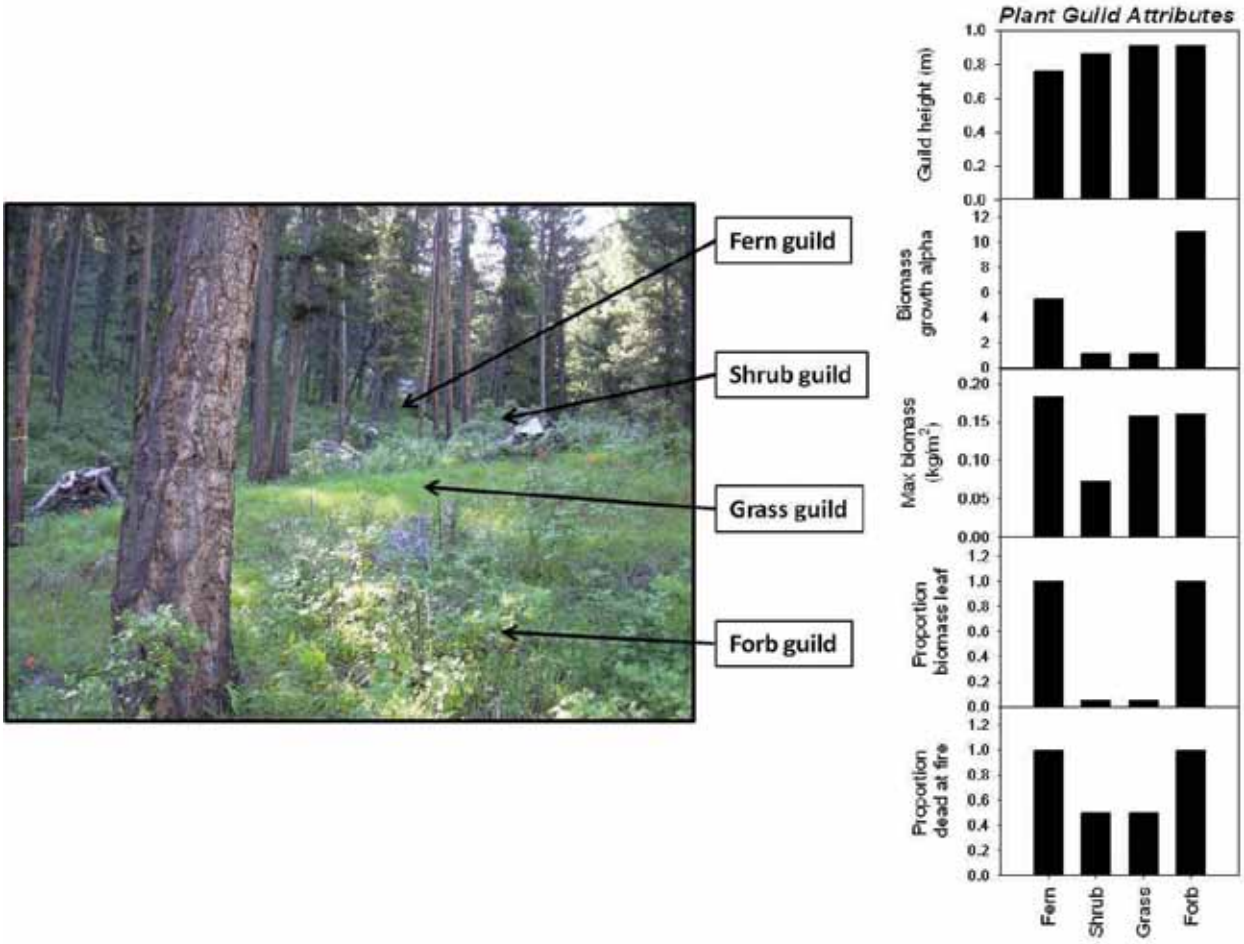

Figure 8. The representation of the undergrowth in FireBGCv2. All biomass in the undergrowth is separated into guilds and parameters used to model each guild are specified in the plant models that are assigned to each site.

FireBGCv2 allows the stratification of undergrowth vegetation into an infinite number of guilds (Figure 8). A guild is a classification grouping of species with similar ecophysiological attributes (plant functional types, for example). The user can input up to 100 guilds in a simulation. This allows individual undergrowth species to be simulated. However, the most parsimonious simulations stratify undergrowth species into ecologically similar groups, such as plant functional types, and simulate changes in biomass within these guilds. A large number of guilds will make the simulation more complex and computationally intensive. We recommend somewhere between 4 and 20 guilds to represent the understory in a simulation landscape.

Parameters for these guilds are stratified by plant models (Figure 9), which are like fuel models in that they describe a group of static parameters that are used across guilds but vary nonetheless in their values across sites. Plant models allow the stratification of important guild parameters by biophysical setting or site. For example, a simulation may include two guilds—herbs and shrubs. The plant model for an alpine tundra site might have the maximum height as 0.02 m for herbs and 0.1 m for shrubs, while the lower subalpine site plant model might have maximum height as 1.0 m for herbs and 1.8 m for shrubs (Figure 9). Again, plant models are assigned by site and not by stand, and the same plant model can be assigned to two different sites. The design of plant models is difficult because of the diverse parameters, so it requires knowledge of forest undergrowth and seral communities. It is suggested to use the same number of guilds for each plant model and that these guilds be roughly equivalent across all plant models. This allows for a more comprehensive interpretation of results across the landscape.

The plant model consists of many parameters. An identification (ID) number, name, and the number of guilds are used to identify plant models during the simulation. The plant model ID number is specified in the Site.in file and is used for all stands within that site. Each guild is assigned values for the following parameters, which will be different across the number of plant models specified in the Plant.in file:

- SppID. Species ID number. This index number references a species in the Species.in file; and when FireBGCv2 needs a species-level parameter for an undergrowth guild, such as SLA, it takes it for that species.
- FuelID. Fuel ID number. This index number references a fuel model in the Fuel.in file, so when FireBGCv2 needs a fuel parameter, such as surface area to volume ratio, it takes it from that fuel model.
- UHT_{max}. Guild height (m). The maximum height of the plants in this guild. This is used to distribute leaf area in the canopy and for fuelbed characteristics.
- ALPHA. Biomass growth rate coefficient (yr^{-1}). The coefficient that defines the growth rate of species in a guild. See "Undergrowth Dynamics" in the "Stand Processes" section for more information.
- $BIOMASS_{max}$ ($kgB\ m^{-2}$). Maximum aggregate biomass attainable for all species in a guild. This is another coefficient that defines the biomass and fuel loading of species in a guild. See "Undergrowth Dynamics" in the "Stand Processes" section for more information.
- $LEAF_{frac}$ (proportion). Fraction of guild biomass that is leaf. This is the proportion of the total biomass that is leaf biomass.
- FDEAD (proportion). Fraction of guild biomass that is dead at the time of a fire. This is used to separate live and dead fuels for this guild for fire simulation.

The user must also name each guild for organizing the Plant.in file and for providing detail in model output.

There are a number of state variables that are used to simulate undergrowth dynamics for each guild. While the parameters above are static, the state variables below are updated at daily and yearly time steps.

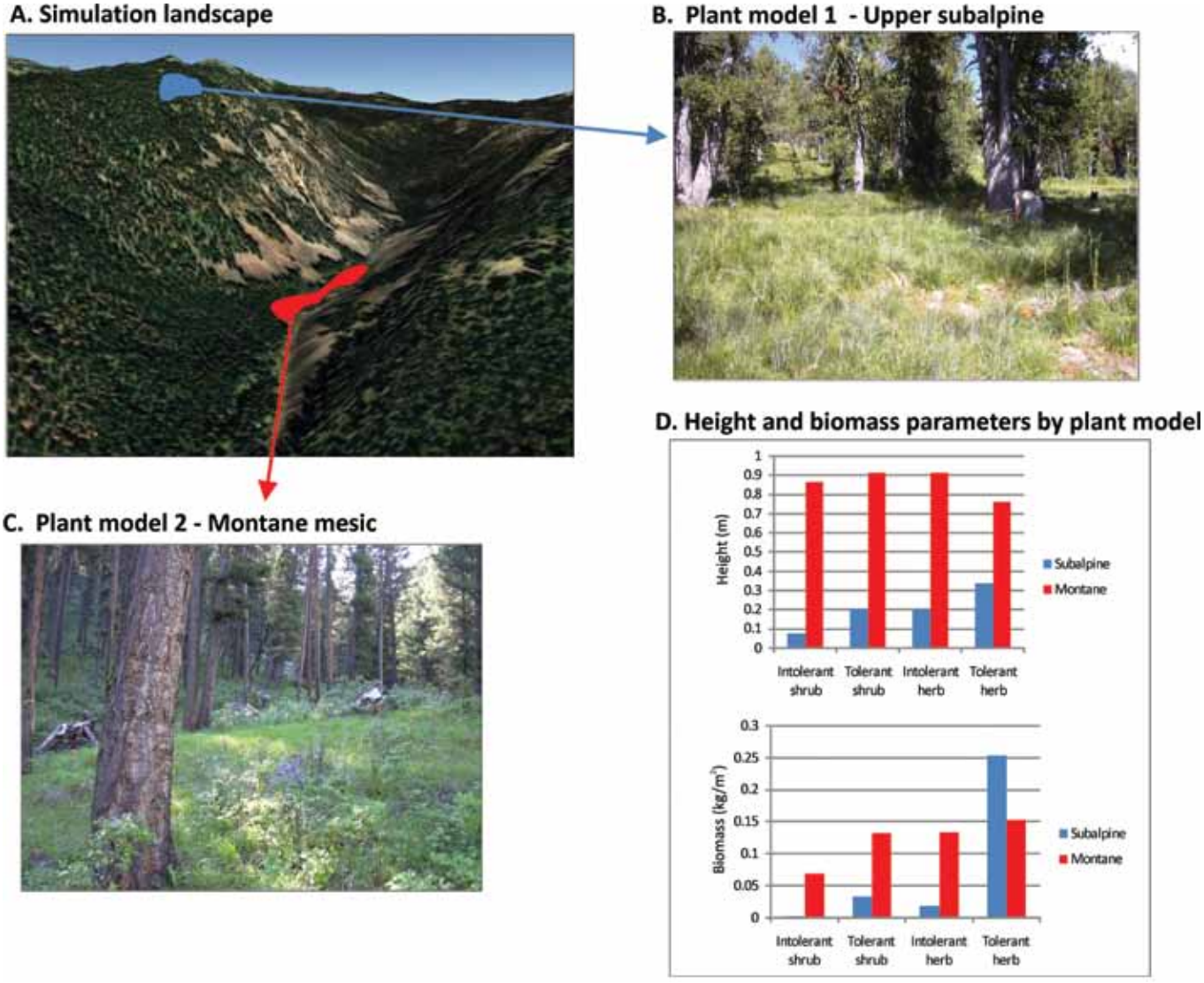

Figure 9. An example of how plant models work in FireBGCv2. A plant model is a special parameterization of plant guilds based on environmental conditions. In a landscape simulation (A), an upper subalpine plant model (B) and a mesic montane plant model (C) are created that have different values for the maximum biomass and maximum height parameters for four guilds in a FireBGCv2 simulation (D).

- BIOMASS (kgB m^{-2}). The instantaneous amount of biomass on the simulation plot for all the plants of the species within the guild.
- $BIOMASS_{gs}$ (kgB m^{-2}). The amount of biomass on the simulation plot for all the plants of the species within the guild at the height of the growing season for that year.
- UHT (m). The instantaneous height of the undergrowth guild.
- ULA (m^2). The instantaneous projected leaf area of the undergrowth guild.
- UPSN (kgC m^{-2}). The amount of carbon from photosynthesis for that guild during that year.
- URESP (kgC m^{-2}). The amount of carbon lost from respiration for that guild during that year
- UNPP (kgC m^{-2}). The amount of carbon gain as growth for that guild during that year.

Biomass was used for the undergrowth guilds instead of kgC to allow for consistency with the fuel and fire algorithms and for interpretation of intermediate results.

Tree Simulation

Trees are represented in the FireBGCv2 program by two types of state variables: structural and pool variables. The structural variables describe the physical aspects of the tree. They include:

- SppID (index). Species index number cross-referenced to the species in the Species.in file
- DBH (cm). Diameter at breast height.
- HT (m). Tree height.
- HBC (m). Height to the bottom of the crown.
- AGE (year). Age of tree.
- LA (m^2). All sided leaf area of the tree.
- RUST (flag). Flag indicating if this tree is rust resistant (RUST = 1).
- YSI (counter, year). Years since mountain pine beetle outbreak.
- STRESS (counter, year). Years of stress.

The carbon pool variables are used to keep track of carbon by pools as needed for a *BGC* simulation (Figures 3 and 4). They are as follows:

- LeafC (kgC). Carbon in leaf biomass.
- $LeafC_{max}$ (kgC). Carbon in leaf biomass at peak of growing season.
- FrootC (kgC). Fine root carbon.
- LivestemC (kgC). Amount of carbon in the live stem, including twigs, branches, and boles.
- DeadstemC (kgC). Amount of carbon in the dead stem, including bark, twigs, branches, and boles.
- LivecrootC (kgC). Amount of carbon in the live coarse roots.
- DeadcrootC (kgC). Amount of carbon in the dead coarse roots.
- PSN (kgC). Amount of carbon fixed as photosynthate during the year for that tree.
- RESP (kgC). Amount of carbon lost to respiration during the year for that tree.
- StemC (kgC). Previous year's stem carbon (live and dead).

Once a tree dies, it becomes a snag and each snag has these state variables:

- SppID (index). Species index number cross-referenced to the species in the Species.in file.
- DBH (cm). Diameter at breast height.
- HT (m). Tree height.
- AGE (year). Age of tree.
- WoodC (kgC). Amount of carbon in the dead wood.

Only AGE and WoodC are dynamic state variables for snags.

Program Flow

The flow of the FireBGCv2 model is somewhat complicated because of the cross-scale design of the program, so it is difficult to encapsulate all of the complexity into one flow chart. But Figure 10 provides sufficient detail to understand the order of FireBGCv2 simulations. First, the program reads all initial values and parameters from a series of input data files that are specified by the user in the Driver.in file. Then, all state and flux variables in the model are initialized with that input information. A comprehensive logic and error check is then performed on all input initial values and parameters to ensure all entered data are compatible

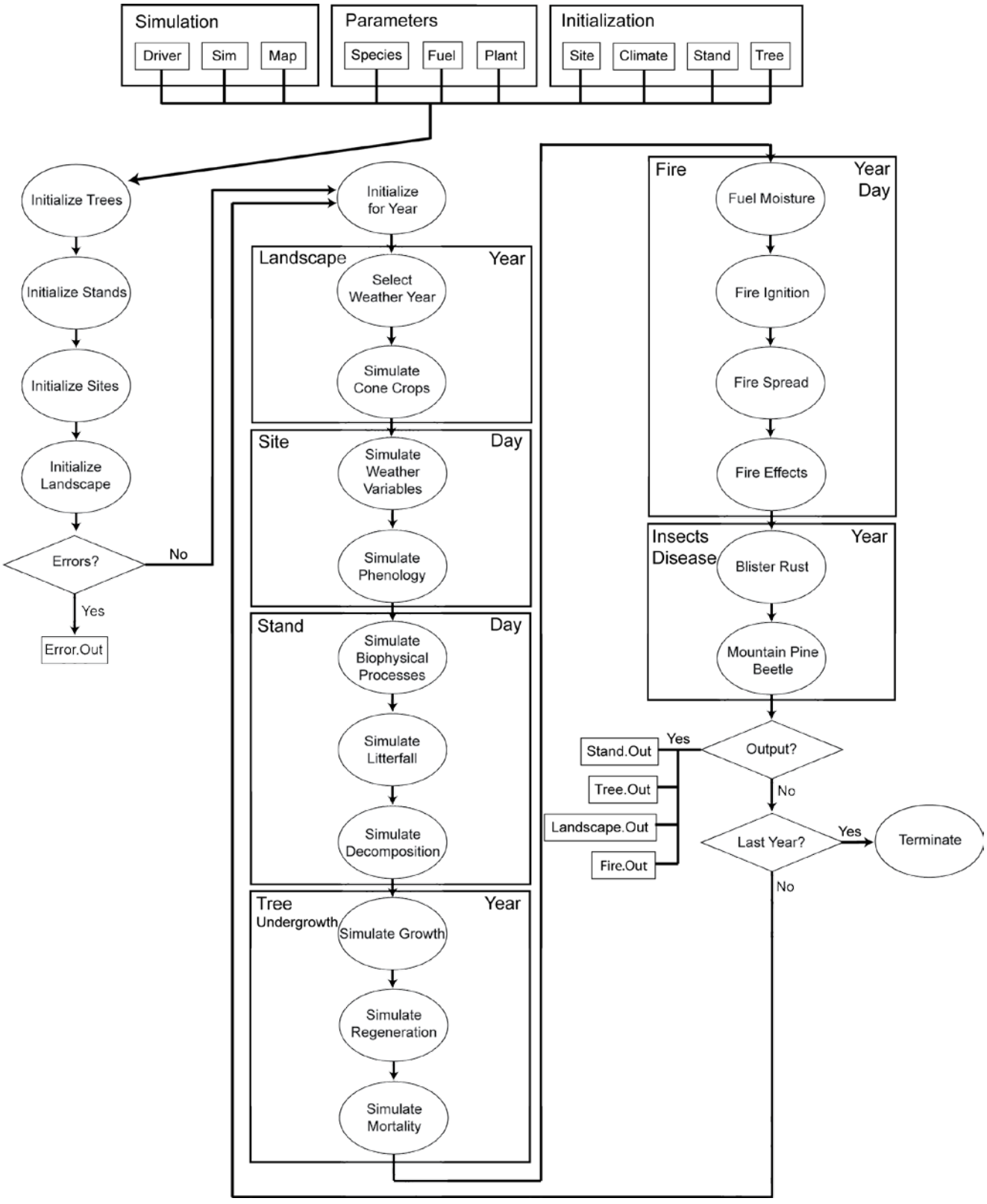

Figure 10. Simplified flow chart of the FireBGCv2 model.

and rectified. This is especially important because this check also ensures critical issues won't emerge after hundreds of years of simulation that could take days in real time. Simulation of all ecological processes now starts from the coarsest scale to the finest scale. For example, spatial processes of cone abundance and seed dispersal are first simulated at the landscape level, plant phenology and fire ignition are simulated at the site level, then water dynamics are simulated at the stand level, and tree growth is simulated at the tree level.

The daily simulation of stand-level processes is then accomplished using the simple gap, mechanistic gap, or *FOREST-BGC* routines. First, weather is input by site from data in a weather file (Figures 3, 4, and 7). Daily photosynthesis, respiration, and water budgets are then calculated to obtain yearly carbon gains. At the end of the simulation year, stand carbon and nitrogen are allocated to each tree in the stand and then to the leaf, stem, and root components of each tree. The carbon allocated to the tree's stem is converted to a diameter growth. Establishment of new trees is then assessed by species in the regeneration routine. The possibility of tree death is evaluated in the mortality algorithm. Then, fire occurrence and subsequent fire behavior and effects are dynamically modeled on the landscape. Forest floor decomposition is simulated daily, the forest canopy characteristics are recomputed at year's end, and the process is repeated for the next year.

Disturbances and their effects are simulated at the end of the year, but many disturbance variables are calculated and summarized at a daily time step. Output is also printed to the appropriate files (.out files) at daily and annual time steps for stand, tree, and fire variables.

Programming Specifics

FireBGCv2 was programmed in the C programming language, but it does not use the C++ class and object structure for a number of reasons. First, we started programming FireBGCv2 in the late 1990s and C++ was only beginning to become popular. At that time, UNIX-based workstations were the only platforms available and none of our workstations had comprehensive C++ compilers and debuggers in a programming environment. The C programming style was primarily selected because it was the easiest to port to other platforms and it offered the greatest balance between speed, compatibility, and interpretability.

The programming style of FireBGCv2 emphasized flexibility, interpretability, and debug-ability rather than high optimization and execution speed. Many functions were written so that other programmers could understand the programming flow and modify code with ease. Instead of combining equations, many algorithms solve in a stepwise fashion so that intermediate results can be evaluated. As a result, FireBGCv2 can be somewhat slow and can consume a great deal of memory. However, it should be relatively easy for a user to read the program's code to determine the logic and flow of any module, even if the user is not a programmer.

Model Algorithms

This section describes the approaches, methods, protocols, and algorithms that FireBGCv2 uses to simulate fire, vegetation, and landscape dynamics. This section is designed as an efficient reference on a particular simulation method rather than a step-by-step description of how the model simulates ecosystem dynamics. The section is organized by spatial scale from broad- (landscape) through progressively finer-scale (site, stand, species, and tree) processes, with the algorithms that simulate ecological processes further organized by the vegetation, disturbance, or biophysical factor simulated. Many processes are simulated across multiple scales; for example, fire ignition and spread are simulated across the entire landscape, fire behavior is simulated for each burned stand, and mortality is simulated for each tree.

General Algorithms

A few general algorithms are used by nearly all model routines in the FireBGCv2 platform. Many ecological processes are simulated in FireBGCv2 using stochastic approaches, and all stochastic approaches depend on a consistent random number generator. The random number generators available in FireBGCv2 were taken from Press and others (2002) and Ecuyer (1988), but extensive tests of these routines revealed some inconsistencies and unwanted behavior. We tested the system-level random number generator in the Microsoft C++ compiler and found its behavior acceptable for long FireBGCv2 runs when the random generator might be called billions of times. In this report, the variable that is used to store the random number (number between 0.0 to 1.0) is always RNUM.

Landscape Processes

Cone Crop

Two aspects of the tree regeneration process are spatially simulated at the landscape level during a FireBGCv2 simulation. First, the occurrence of an abundant cone crop is stochastically determined for each tree species in the simulation for the entire landscape. Then, the spatial dispersal of the seeds from that cone crop is simulated by species across the landscape. Again, these spatial processes are fully linked with stand-level processes through the storage of intermediate information and dynamic databases.

Each year a tree species can have a good or poor cone crop. Tree regeneration only occurs in good cone crop years. Species' cone crop abundances are stochastically modeled at the landscape level rather than the stand level because the processes that govern cone production, such as climate and topography, work at the coarser spatial scale (Boe 1954, Eis and Craigdallie 1983, Piovesan and Adams 2001). Cone crops are simulated by comparing a generated random number (RNUM) to the probability of a good crop for a species (PCONE) and if RNUM is less than PCONE, a good cone crop is initiated. This Monte Carlo stochastic method is based on the approach used by Kercher and Axelrod (1984) in their *SILVA* model and Keane and others (1990b, 1990c) in *FIRESUM*. The chance of having a good cone crop in subsequent years is blocked for a number of years (NOCROP, specified by the species in FireBGCv2) based on the assumption that trees must store sufficient energy reserves before generating another good cone crop. Future versions of FireBGCv2 will mechanistically simulate cone crops based on carbon budgets, climate events, and tree health once sufficient research has been conducted.

Seed Dispersal

The relative probability of a seed falling onto a stand is computed in FireBGCv2 by calculating the amount of seed available for dispersal from stand species composition and density and then dispersing the relativized seed totals across all pixels in a landscape using seed dispersal curves following methodologies in Kellomäki and others (1987), Ribbens and others (1994), Greene and Johnson (1996), and South (1999). First, the probability of seed dispersal to every pixel in the landscape is computed using this relativized form of the equations of McCaughey and others (1986):

$$P_{dist} = \frac{e^{[a + bDIST]}}{e^{[a]}} \quad (1)$$

where P_{dist} is the probability of a seed landing on a pixel, DIST is the distance between the seed source pixel and target pixel (m), and a and b are equation coefficients by species from McCaughey and others (1986) (Table 3).

The above equation is for tree species whose seeds are dispersed by the wind. The probability of seed dispersal of the bird-disseminated whitebark pine seed is calculated from the equation of Tomback and others (1990):

$$P_{dist} = \frac{10^{[0.8062 - 0.000454DIST]}}{0.1563} \quad (2)$$

Calculating the spatial distribution of P_{dist} for each tree species across the landscape involves a "moving window" approach where a source pixel is selected (starting in the northwest corner of the simulation landscape) and the model obtains stand-level information for this pixel. The distance (DIST) from this source pixel to all other target pixels on the simulation landscape is calculated using the Euclidean distance formula ($X^2 + Y^2 = DIST^2$) until the distance to target pixel yields a P_{dist} less than 0.001. Then, another source pixel is selected, and the procedure is repeated for all landscape pixels as targets. This process is reiterated for all pixels as sources with the calculated P_{dist} summed for each pixel. The sum of all computed P_{dist} is divided by the number of iterations and across all pixels in a stand to calculate an average P_{dist} for each stand.

The size of the cone crop is represented by the number of cone-producing trees per hectare ($SEEDTREE_i$) by species *i* for the stand. SEEDTREE is calculated from the previous simulation year's stand information by summing all trees in a stand that are greater than 10 cm in DBH and greater than the minimum species

Table 3. Seed dispersal parameters for the species in the FireBGCv2 model for the northern Rocky Mountain simulations.

Species	Parameter a	Parameter b
Pines (ponderosa)	13.1251	0.0255
True firs, yews	13.4099	0.0183
Douglas-fir	14.1251	0.0222
Lodgepole pine	12.6760	0.0376
Western larch	14.3257	0.0148
Subalpine fir	13.4099	0.0183
Spruces	12.7470	0.0251
Limber pine	12.7470	0.0251
Western white pine	14.3257	0.0148
Western red cedar	13.1251	0.0257
Western hemlock	11.9823	0.0297
Aspen, cottonwood	12.9129	0.0079

reproductive age ($AGECONE_i$) by species *i*. This sum is then scaled from 0.0 (no trees producing seeds) to 1.0 (five or more cone-producing trees per hectare) and stored in a reduction variable (rTREE). Then, P_{dist} is multiplied by rTREE for every calculation and iteration above to adjust for limited seed source production.

The simulation of seed dispersal is computationally intensive because of the numerous and iterative moving-window computations. As a result, it is recommended that this computation only be performed every decade or two (user defined in the Sim.in file as SEEDOPT). The model will automatically update seed dispersal probabilities if more than 10 percent of the landscape has changed as a result of disturbance, such as fire or insects. To save time, we also recommend that the initial seed dispersal probabilities be saved in a file so that the seed dispersal module need not be invoked to initialize seed dispersal parameters. The seed dispersal output file must be specified in the Driver.in file as seeddisp.dat, and the option to use initial dispersal probabilities is specified in the Sim.in input file.

Effects of topography, wind, seed size, temperature, and predation on seed dispersal are not included in the FireBGCv2 platform (Venable and Brown 1988, Greene and Johnson 1995, Clark and others 1999, Groeneveld and others 2002). Although these are important interactions that must be modeled across spatial scales to fully account for species migration across a landscape, especially in the context of climate change, their implementation may overwhelm computing requirements and cause major problems with simulation times and memory requirements. Future versions of FireBGCv2 will implement these dynamics within dispersal routines once simulation technology has advanced.

Wildland Fire

The process of wildland fire actually occurs at multiple scales. Fire ignition and spread are simulated in FireBGCv2 at the landscape scale. Ignition is determined by the input fire frequency probability at the site level and by the amount of ignitable fuel at the stand level, but the actual simulation of fire starts occurs across the entire landscape. Spread is a true landscape process because it is simulated across sites and stands based on landscape-level attributes (wind and slope) as well as stand-level attributes (fuel availability). Fire behavior is simulated at the stand level along with the fire effects of consumption and smoke while fire-caused tree mortality is simulated at the tree level. This may be confusing for many but it is important to know that several major disturbance processes in FireBGCv2 are simulated at multiple scales to rectify and organize landscape dynamics.

Fire Ignition

The frequency of ignition and points of origin of simulated fires are stochastically predicted at a yearly time step across the simulation landscape. The entire ignition simulation algorithm scales stand-level fire occurrence based on the site-level fire return intervals (year) that are input by the user in the Site.in file to compute an instantaneous probability of fire occurrence for that site (Keane and others 1989). This probability is then scaled to the size of the stand, level of fire management, and climate using the procedure detailed below. This procedure is done each year for every stand by site on the simulation landscape.

The first factor evaluated in this algorithm is the burnability of a stand, or the potential for a stand to have an ignition. This is determined from the amount and type of fuel on the ground. The biomass from all flashy ground fuels (litter, twigs, small branches, and current year's leaffall; see "Stand Processes" section) is summed for the stand and compared to a threshold value called minimum fuel loading or MIN_FUEL_LOADING (in FireBGCv2, the minimum fuel loading is 0.05 kgB m^{-2} based on simulations in the Behave program). If the flashy biomass is greater than MIN_FUEL_LOADING, the stand is then considered burnable and a fire ignition is allowed to occur within the stand. If the amount is less than the threshold, then the biomass in the undergrowth guilds is summed for the stand

and compared against the MIN_FUEL_LOADING in a similar manner to the flashy ground fuels. A fire is not allowed to burn in the stand if both the flashy and undergrowth biomass in a stand are below the threshold.

Fire ignition on burnable stands is simulated from a probability of fire occurrence (P_{fire}) that is computed by first using a base fire probability that is input to the model in the Site.in file and scaling it to account for several environmental factors, such as the area of the stand, climate for that year, and level of fire suppression effort. There is an option in FireBGCv2 where the base P_{fire} can be computed from a form of the Weibull equation hazard function:

$$P_{fire} = \left[\frac{a}{FRI_i}\right]\left[\frac{YSB - REBURN^{a-1}}{FRI}\right] \quad (3)$$

where YSB is the years since a stand last burned, REBURN is an input parameter in Site.in file for the number of years before this stand can burn again, FRI is the site-level input value for fire return interval (year), and *a* is the shape function (value of 2.0 in FireBGCv2). This algorithm is based on the equations and algorithms presented in many studies (van Wagner 1978, Johnson and van Wagner 1985, Baker 1989, Fox 1989, Clark 1990). However, we found that the most stable method of computing P_{fire} is to simply take the inverse of FRI (Keane and others 1996). We feel this estimation for P_{fire} behaves best across a diverse number of ecosystems and topographical conditions (Keane and others 2006).

This base probability P_{fire} is then adjusted for scale to account for fire size using the following relationship:

$$rFIRE = \frac{AREA_j}{FSIZE_i} \quad (4)$$

where rFIRE is a reduction variable that can range above 1.0 in some cases, $AREA_j$ is the AREA (m^2) of stand *j*, and FSIZE is the average fire size (m^2) for the site *i* where stand *j* resides, which is input to the model in the Site.in file (Marsden 1983, Reed 1994).

We explored many approaches for integrating climate into fire ignition processes from relating fire danger and fuel moisture variables to fire activity (Hargrove and others 2000) to simulating fire regimes from climate parameters (Gardner and others 1997, Cary 1998, Keane and others 2004b). In the end, we found the most scalable, simple, consistent, and realistic approach was to simulate climate effects on fire ignition using deviations from the site's fire weather based on a fire index, namely the Keetch Byram Drought Index (KBDI) (Keetch and Byram 1968, Burgan 1993). At the beginning of a FireBGCv2 simulation, the KBDI is computed for every day in the site's input weather stream and the maximum KBDI ($KBDI_{base}$) is computed for the fire season (Julian dates 179 to 269) across all years. The variable rCLIMATE is then computed as the scale of current KDBI to base KBDI (rCLIMATE = KBDI / $KBDI_{base}$). Refer to "Weather" in the "Site Processes" section to understand how to compute KBDI.

The effect of wildfire management is included as an input parameter in the FireBGCv2 Sim.in file that is constant throughout the simulation run. The fire suppression reduction variable rMGT represents the level of effectiveness of the fire suppression effort. This variable is computed from the equation 1 - FIRESUPP where FIRESUPP ranges from 0.0 (no suppression) to 1.0 (total suppression) and is specified as a simulation input parameter in the Sim.in file.

The final probability of fire P_{fire} is then computed from the multiplication of all factors with the base probability:

$$P_{fire} = P_{fire}(rCLIMATE)(rFIRE)(rMGT) \quad (5)$$

The stand's final fire probability (P_{fire}) is then compared to a freshly generated random number (RNUM) and a fire start is simulated for the stand in question

if RNUM is less than P_{fire}. FireBGCv2 randomly selects one of the pixels in the stand as the ignition point for the fire. The locations of this pixel and any other pixel that has a simulated fire start are stored until the end of the simulation year, when they are passed to the fire spread routine to simulate the perimeter of the fire.

Fire Spread

The spatial process of the spread of a fire across the landscape is somewhat problematic for landscape fire regime models because of the intense computational demands required over the long simulation times and large simulation areas. Some large, fire-prone landscapes can have many fires in a single year, and since spread algorithms can be quite complex (Gardner and others 1999), the simulation of spread from multiple fires can often overwhelm available computing resources. We tried many fire spread algorithms from the highly mechanistic, detailed vector spread algorithms in the *FARSITE* model (Keane and others 1997, Finney 1998) to the more simplistic cell automata spread models (Karafyllidis and Thanailakis 1997, Barros and Ball 1998). Detailed spread routines often lengthened simulation times by an order of magnitude, while simplistic spread models produced fire perimeters that were often unrealistic. We settled on the cell percolation approach that was implemented in the *LANDSUM* model (Keane and others 2002a) because it was computationally efficient yet still seemed to produce realistic fire perimeters. This approach uses vectors of wind (input to the model in the Site.in file) and slope (computed in FireBGCv2 from the input digital elevation model [DEM]) to drive fire spread. There is a slot in FireBGCv2 to add a more mechanistic, highly efficient fire spread algorithm such as *FARSITE,* and there also is a cell automata model implemented in FireBGCv2. However, we feel that the cell percolation spread model provides the best balance between realism and computational demand.

In the cell percolation model, fire is spread across the landscape at the pixel level using directional vectors of wind and slope. Wind direction (degrees azimuth) is an initial input to the model by site, but then it is randomly modified within 45 degrees of the input direction for each simulated fire. Wind speed (m sec^{-1}) is also an input parameter that is randomly adjusted within 0.5 times of a user-specified input value for each fire. Slope (percent) is computed by pixel from the input DEM. The fire spreads to pixels in eight possible directions (N, NE, E, SE, S, SW, W, NW), as calculated from the following relationship modified from Rothermel (1991):

$$SPIX = (WIND_f)(SLOPE_f) \quad (6)$$

where SPIX is the number of pixels to spread in a direction, and $WIND_f$ and $SLOPE_f$ are wind and slope factors that are computed from the following equations:

$$WIND_f = (1+0.125\omega)(\cos(abs(\theta_s - \theta_w)))\omega^{0.6} \quad (7)$$

$$SLOPE_f = \frac{4}{(1 + 3.5e^{10\Delta})} \quad (8)$$

where ω is wind speed (m sec^{-1}), *abs* is absolute value, θ_s is the spread direction (azimuths), θ_w is the wind direction (azimuths), and Δ is slope (percent, rise over run) (Rothermel 1991). The slope factor above applies to only positive slope values (upslope spread). Down-slope spread is computed as:

$$SLOPE_f = e^{3\Delta^2} \quad (9)$$

These equations are solved for each pixel ignited by the fire, originating from a randomly selected fire start pixel, as mentioned above. Only pixels that have an FRI shorter than the simulation time period are allowed to burn, except for patches where P_{fire} is zero, such as in a recently burned patch. Rounding of the computed SPIX to the nearest pixel size (30 m for most simulation studies) is stochastically determined from a uniform random number generator. Initially, fires were allowed to burn until they hit the landscape boundary or an unburnable patch (no fuel), but this resulted in too much area burning on the simulated landscapes. We then limited fire spread by stochastically calculating a maximum fire size (FIRESIZE, m^{-2}) for each fire from the following fire size distribution equation:

$$FIRESIZE = \alpha \ln(RNUM)^{\beta} \quad (10)$$

where α is the magnitude parameter that is approximated from average fire size (m^{-2}) and is specified in the Site.in input file, RNUM is a random number from a uniform probability distribution, and ß is a shape parameter estimated as 3.0 in FireBGCv2 (Keane and others 2002a). Average fire size can be estimated from fire records (Schmidt and others 2002) or from previous studies (Cui and Perera 2006). Fire growth is simulated until the size of the fire exceeds FIRESIZE, and the final size is stored to calculate landscape fire rotation over the simulation time period so users can adjust their critical fire inputs, average fire size (α) and FRI to simulate realistic fire regimes under historical climates. Fire spread is simulated at the end of the model year using weather from that year.

Insects and Diseases

Mountain Pine Beetle

There are two variables in the Sim.in file that must be set by the user to simulate an insect (mountain pine beetle) or disease (blister rust) outbreak in FireBGCv2. The BEETLE and RUST variables are initialized as simulation parameters in the Sim.in file. They are important because they specify if and when an insect or a disease epidemic occurs. The user assigns a value to these variables that indicates what year the simulation of an outbreak would start, and the model does not simulate insect/disease dynamics until that year. For rust, if the sign of the variable is negative (-200, for example), the program will start the rust epidemic on the absolute value of the negative number (year 200, for example), but it will also assume that all dead five-needle pine trees (whitebark, limber, and western white pine, for example) that were entered into the Tree.in file will be live trees instead of snags so that historical stand dynamics can be modeled.

The initiation of a mountain pine beetle epidemic is simulated at the landscape level at an annual time step using algorithms in Cole and others (1985). First, the number of days when the average daily temperature was below -20 ^{o}C (NFREEZDAYS) and below -40 ^{o}C (NFROZDAYS) are summed across the entire year of simulation for every site on the landscape. Then, if NFREEZDAYS is less than 11.0 or NFROZDAYS is less than 1.0 for a site, the area (m^2) of the site is summed (SITEAREA) and a counter (YSFREEZE) is incremented one year. The model also evaluates the proportion of the landscape that is occupied by available hosts of the mountain pine beetle (MPBHOST_AREA, percent). This is computed as the sum of the area of stands that have greater than 30 percent of the stand's basal area (m^2 ha^{-1}) in pine trees that are larger than 20 cm DBH divided by the area of the entire site on the simulation landscape (without the buffer). The resulting number is then multiplied by 100 to get the percent of landscape in host trees.

The program sets a flag (MPB_FLAG) for a site if the number of years without a lethal freeze (<-20 ^{o}C for 11 days, <-40 ^{o}C for 1 day) is greater than 40 years and the proportion of the site in host species (MBPHOST_AREA) is greater than

40 percent. Once the flag is set, the model will simulate an endemic beetle outbreak for that site using a set of modified mountain pine beetle mortality equations (discussed in the "Tree Processes" section). The model simulates a mountain pine beetle epidemic if these two conditions are met: (1) the area (over all sites) that has host species is greater than 40 percent summed over all sites or is greater than 40 percent for the entire landscape, and (2) the summed area for those sites that have favorable weather (YSFREEZE > 40) is greater than half the landscape. In an epidemic, all pines above 20 cm DBH are assigned a 0.99 probability of beetle-caused tree mortality (see the "Tree Processes" section).

White Pine Blister Rust

Rust epidemics are simulated in FireBGCv2 using a simplistic method taken from McDonald and others (1981) and Howell and others (2006) that is based on whether appropriate conditions for rust infection occur during the autumn (defined as Julian days 230 to 260). The model averages relative humidity and temperature over this range of Julian days for each site, and if the average relative humidity is above 70 percent and mean temperature is above 10 ^{o}C, a rust flag is set at the site level (RUST_FLAG), indicating a rust infection year. When simulating tree mortality, the model checks to see if the rust flag is set to YES, and if so, the probability of mortality is set to 0.99 for rust-susceptible five-needle pines. The program determines rust resistance (susceptibility) at the beginning of a simulation by randomly assigning a percent of the trees to be rust resistant—they will not experience rust mortality throughout their lifetime. That percent is currently assigned at 1.0 percent in the code, but future versions will allow rust resistance to be assigned by the user by species.

Management Actions

Three types of management actions or treatments are implemented in FireBGCv2—clearcut harvest, partial-cut harvest (thinning, selection, and seed tree, for example), and prescribed burning. Both the clearcut and partial-cut harvest actions allow prescribed burning as another post-cutting treatment. The details of the management actions are specified in the Manage.in input file. All management actions take place at landscape- and stand-level scales. The landscape-level information is used to determine if a treatment should be implemented, and stand-level information is used to decide which stands should be treated and how the treatments should be implemented based on the stand's condition. The following describes how the model decides if a treatment should be implemented.

Within the Manage.in input file, a set of parameters (ALIMIT, BLIMIT, CLIMIT, DLIMIT) called *treatment limits* dictate whether and when a treatment should be implemented on the landscape and for a particular stand. For all three treatment types, the ALIMIT parameter is the total landscape area (ha) allowed to be treated each year. For example, if the user enters 100 for the ALIMIT for partial cutting, the program cycles through all sites and stands and treats those stands that meet a user-defined selection criteria until the total stand area treated reaches the 100 ha threshold. The BLIMIT parameter specifies the largest stand size (ha) that can be treated. If a stand area is greater than BLIMIT, no treatment will be implemented, even if the stand otherwise meets the selection criteria. This may limit treatment options within the simulation if a simulation landscape is initially built with large stands to optimize simulation resources. The CLIMIT parameter defines the minimum basal area (m^2 ha^{-1}) that a stand must have to be treated with cutting treatments, and the minimum number of years since last fire with the prescribed burning treatment. The DLIMIT parameter specifies the lower DBH (cm) threshold for partial cutting treatments, but is not used for clearcut treatments. For prescribed burning, the DLIMIT parameter is a factor that, when multiplied by the stand's site FRI (year), specifies the minimum number of years before the stand can be treated again by prescribed burning. The program cycles

through sites and stands in the order that they are listed in the Site.in and Stand.in input files, respectively, and then applies the above criteria to each stand to decide which to treat and when there is enough treatment on the landscape for each year. There will be many years when no treatments are implemented. These are the only activities that are done at the landscape level. The treatments are implemented at the stand level (see the "Stand Processes" section).

Hydrology

Streamflow hydrology has only recently been implemented in FireBGCv2 as an optional module that is invoked only when the simulation of the hydrologic cycle and water resources is desired. This is accomplished by identifying a site biome (BIOME) as a "riparian" site using the number 5 in the Site.in file. If a riparian site is specified in the Site.in file, then the hydrological routing model is initiated, and a specialized set of algorithms is used to estimate streamflow across all the streams on the landscape. This hydrologic routing module was included so that we could empirically compute stream temperatures, which require estimates of streamflow, air temperature, elevation, solar radiation at the stream surface, stream channel slope, and area in basin that contributes water to streamflow. Stream temperature simulation also allows subsequent estimations of fish survival and productivity. The hydrology algorithms are computationally intensive and require extensive memory, particularly for large landscapes with extensive stream networks, so it is recommended that the hydrology module only be used if streamflow and stream temperatures are desired.

We had to implement a somewhat simplistic hydrologic flow model into FireBGCv2 because of computational, memory, and data requirement concerns. We used a deterministic hydrologic process modeling approach rather than a stochastic data-based approach to facilitate empirical estimates of stream temperature that use streamflow as input. For our process-based approach, we implemented a hydrologic routing model that contains representations of surface runoff, subsurface flow, and channel flow (Srinivasan and others 1998; Zeleke and Si 2005) with FireBGCv2's mechanistic water balance model that simulates evaporation, transpiration, soil water content, and outflow (Keane and others 1996a) (see the "Stand Processes" section).

One major requirement for a hydrological routing simulation is that the simulation landscape (excluding the buffer) must completely encompass a watershed because the model assumes that all water that falls within this simulation landscape is routed to the stream and ends up exiting from the landscape at the lowest point; the simulated flow at this exit point can be compared to stream discharge hydrographs to calibrate and validate FireBGCv2. A complex digital map is required as input for all hydrological simulations, and this layer (called *distance to stream*) has pixels that are assigned a positive value for upland areas and contain the values for distance (m) to the nearest stream along flow paths from that pixel and the elevation difference between that pixel and the nearest stream (m) with the format YYYYXXXX where YYYY is the elevation difference along a flow path (HEAD, m) and XXXX is the distance to stream (DTS, m). All pixel values that are less than zero (the streams) have three stream attributes combined into one value. This stream pixel value has a format of –XYYY.ZZZ, where the negative sign tells the program that this is a stream pixel (upland, non-stream pixels are positive), the X indicates the stream order (SORDER; value from 1 to 7), YYY represents the stream width (SWIDTH) in tenths of meters (123 is 12.3 m wide), and ZZZ indicates the percent of total simulation area from which this stream pixel is gathering water (percent contributing area or PCA; 123 indicates that 12.3 percent of the watershed is contributing water to this stream pixel). All of these values can be computed using GIS software.

The hydrologic routing model tracks the distribution of water through the ecosystem to the components of soil, subsurface flow, or surface flow. Precipitation

from rainfall and snowmelt to a stand is first evaluated for loss to evapotranspiration and then infiltration to the ground. When the ground soil becomes saturated, the excess water (OUTFLOW) from the stand is shunted to the stream either as overland surface flow (OSFLOW, kgW day^{-1}) or as subsurface flow (SSFLOW, kgW day^{-1}). Specifically, any amount of water that exceeds soil saturation is allocated first to subsurface flow. Excess water can percolate through the soil layer during the day if the water falls as rain. This amount of subsurface water is calculated using the site's soil hydraulic conductivity (m day^{-1}), as calculated from the following Shevnin and others (2006) equation:

$$HC_{soil} = (0.00072)PCLAY^2 \quad (11)$$

where HC_{soil} is the hydraulic conductivity of the soil layer and PCLAY is the percent clay in the soil profile (see the "Site Processes" section). HC_{soil} is then converted to kgW day^{-1} and compared against the amount of total excess water (OUTFLOW). If HC_{soil} is less than OUTFLOW, all water goes into subsurface flow (SSFLOW, kgW day^{-1}), but if HC_{soil} is greater than OUTFLOW, the difference of HC_{soil} - OUTFLOW is allocated to SSFLOW, and all remaining water goes into surface flow (OSFLOW, kgW day^{-1}). If any SSFLOW and OSFLOW values are greater than zero, their daily discharge values are stored in memory by stand for computation of hydrologic flow processes at the end of the year.

At year's end, FireBGCv2 invokes the routing model that incrementally evaluates each pixel within the simulation landscape (watershed) and then goes through stored daily SSFLOW and OSFLOW values and shunts that daily water to the stream and then out of the watershed. We assume that once this water enters the stream, it will leave the watershed the same day. Water is routed to the stream by calculating how long it will take to enter the stream from the current day (JDAY, Julian date), estimating the day in the future that the water will arrive at the stream, and then adding that discharge amount into a daily stream flow array (STREAMFLOW, kgW day^{-1}) for the estimated day. STREAMFLOW on JDAY is the amount of water that leaves the watershed on the Julian date.

The time it takes for surface water to enter the stream (DAY, days) is calculated using the following relationship taken from USDA-NRCS (1986):

$$DAY = \frac{a[(R)(cDTS)]^{0.8}}{bHEAD^{0.4}} \quad (12)$$

where R is roughness, DTS is distance to stream (m) as taken from the input data layer, HEAD is the elevational fraction between the pixel where the surface water originates and where it enters the stream (m m^{-1}), and *a*, *b*, and *c* are coefficients taken from USDA-NRCS (1986). Roughness is approximated at 0.07 for stands with substantial duff and litter layers (> 0.5 kgC m^{-2}), 0.17 for low duff and litter (between 0.1 and 0.5 kgC m^{-2}), and 0.37 for no duff.

The time it takes subsurface water (SSFLOW) to reach the stream (DAY, days) is calculated using the following relationship for subsurface flow:

$$DAY = \left(\frac{SDEPTH}{HC_{soil}}\right) + \left(\frac{DTS}{(HC_{sub})(HEAD)}\right) \quad (13)$$

where SDEPTH is soil depth (m), HC_{soil} is soil hydraulic conductivity, as previously calculated, DTS is distance to stream (m) from this pixel to the nearest stream along the best flow path as input using the digital input layer described above, HC_{sub} is the hydraulic conductivity of the subsurface soils layers (m day^{-1}) (estimated as a default value of 100 m day^{-1} but adjustable in the Sim.in file), and HEAD is the stream head (m m^{-1}). The first term in the above equation estimates the time it takes for water to go through the soil layer into the subsurface soils layers, while the second term is how long it takes for water to get to the stream once it hits the subsurface layers. HEAD is taken from the stream map for a grid position.

Discharges from surface and subsurface flow amount are added to the streamflow array (STREAMFLOW) in the position of JDAY + DAY. The daily additions from all pixels are then summed into the appropriate days in the STREAMFLOW array. Streamflow out of the simulation watershed can then be estimated for any given day as the JDAY element in the STREAMFLOW array. The STREAMFLOW array has storage for 10 years into the future or 3650 days.

Streamflow for any stream pixel (pixels with a negative value in the *distance to stream* input data layer) for any day of the year is computed by multiplying the STREAMFLOW value for the day in question (JDAY) by the percent contributing area (PCA) and dividing by 100. This pixel streamflow value, in addition to air temperature, stream elevation, solar radiation reaching the stream, elevation, stream channel slope, and the area within the drainage basin that contributes water to streamflow are used to calculate daily stream temperature, trout habitat (using stream width SWIDTH and stream order SORDER), and trout productivity (g day^{-1}) in modules that are scheduled to be added in the future.

Site Processes

Climate

The FireBGCv2 model employs a simplistic method for simulating climate change across the landscape, and it is based on a number of approaches that modify historical daily weather to obtain future weather sequences (Malanson and Westman 1991, Botkin and Schenk 1996, Cary and Banks 1999, Schwalm and Ek 2001). The advantage to this approach is that it is scaled to the input weather record, and all input and simulated weather variables are compatible for any given day. The disadvantage is that the potential increases in climate variability, which are important observed and predicted components of climate change, are not directly included in the FireBGCv2 algorithms (Ibanez and others 2007, Sherriff and Veblen 2008). In FireBGCv2, new climates are simulated by modifying the input site-level weather file on a daily basis to obtain a new weather stream. For example, in a possible climate change scenario, the daily maximum temperature (T_{max}) may be increased by 3 ^{o}C for a selected season and ramped up over a user-specified number of years.

Within the FireBGCv2 Climate.in input file, the user can specify up to six seasons that are defined by the range of Julian days in the season. Under climate change scenarios, maximum and minimum daily temperature, obtained from the input daily weather stream (see the "Weather" section for a complete discussion of the input weather variables), are offset by a user-defined number of degrees. The precipitation variable (PPT) is modified through use of a multiplier; for example, a PPT value of 1.25 corresponds to a 25 percent increase in precipitation for a particular season, and a PPT value of 0.75 corresponds to a 25 percent decrease in precipitation. Vapor pressure deficit (VPD) and solar radiation (SRAD) can also be modified through the use of a multiplier, but because these are rarely summarized in climate change scenarios from Global Circulation Model output, most climate change simulations will use the same radiation and vapor pressure deficit as the historical record.

The user must first specify a starting and ending simulation year of climate change over which the FireBGCv2 model incrementally modifies temperature, humidity, precipitation, and radiation. Prior to the starting climate change year, the weather record is used in its unmodified state. But, following the ending year, the weather record is fully modified by the parameters defined in the Climate. in file. For example, if the starting and ending years of climate change scenario are 1 and 100, respectively, and the T_{max} offset is 3.0 ^{o}C for the summer season, the model will increase daily T_{max} by a factor of 0.03 (1/100 years*3.0) for the first year, and will continue that incremental increase for the next 99 years of the simulation.

There is also a set of parameters that define starting and ending values for three important climate and land use change variables. These parameters are increased across the entire year, not simulated by season. The carbon dioxide concentration (ppm), nitrogen deposition rate (kgN m^{-2} $year^{-1}$), and nitrogen fixation rate (kgN m^{-2} $year^{-1}$) are specified for the beginning and end of the climate change scenario. Each is proportionally modified during the start and end year of the climate change scenario, as discussed for the daily weather variables.

Weather

Core Weather Variables

A daily weather data file is specified for each site that is included in a FireBGCv2 simulation. This file contains daily weather data for all years taken from a weather station at or near each site. The best and most common method used to create this weather file is to use the Mountain Climate Model, *MT-CLIM*, (Running and others 1987, Hungerford and others 1989) to extrapolate weather from a base weather station to a site in mountainous terrain. *MT-CLIM* extrapolates daily temperature (minimum and maximum, ^{o}C) and precipitation (cm) values recorded at valley base stations to mountainous locations based on elevation, slope, and aspect. Values computed by *MT-CLIM* and used by FireBGCv2 are minimum air temperature (T_{min}, ^{o}C), maximum air temperature (T_{max}, ^{o}C), precipitation (PPT, cm), vapor pressure deficit (VPD, Pa), net daily canopy shortwave radiation (SRAD, W m^{-2} day^{-1}), and daylength (DAY, seconds).

At the beginning of each simulation, FireBGCv2 reads and stores the six daily input weather variables (T_{max}, T_{min}, T_{day}, VPD, PPT, and SRAD) for all sites. Then, it randomly selects a weather year to use for all sites, and that daily weather data for that year is used to simulate ecosystem processes in all stands within that site. The user can decide if the sequence of weather years is random or identical to that in the weather file. The FireBGCv2 program will cycle through this weather record until the end of the simulation if the weather year sequence is the same as the input data, or it will randomly pick a year for each year of the entire simulation.

Many other core weather-related variables are computed from the five *MT-CLIM* weather variables (T_{max}, T_{min}, VPD, PPT, and SRAD). Average daily air temperature (T_{ave}, ^{o}C) is computed from an arithmetic average of T_{min} and T_{max} (^{o}C). Soil temperature (T_{soil}, ^{o}C) is computed as an 11-day running average of T_{ave} and is initialized at the beginning of a simulation at 0 ^{o}C. However, when there is snow on the ground, the soil temperature changes with the difference between average annual T_{air} and the previous day's soil temperature multiplied by 0.83 (Running and Coughlan 1988). Average daytime air temperature (T_{day}, ^{o}C) is computed from the following empirical equation from Running and Coughlan (1988) in *MT-CLIM*:

$$T_{day} = T_{ave} + [0.212(T_{max} - T_{ave})] \quad (14)$$

Average nighttime air temperature ($T_{night,}$ ^{o}C) is computed as an average of daytime and minimum temperatures ((T_{day} + T_{min}) / 2.0) and is used to compute nighttime respiration.

A daily average relative humidity (H_r, %) is computed from the following relationship detailed in Campbell (1987):

$$H_r = 100\left[\frac{6.1078e\left(\frac{17.269T_{dew}}{237.3 + T_{dew}}\right)}{6.1078e\left(\frac{17.269T_{ave}}{237.3 + T_{ave}}\right)}\right] \quad (15)$$

where T_{dew} is taken from the VPD value that was computed in *MT-CLIM* (Campbell 1987).

Net radiation to the site (R_n, kJ m^{-2} day^{-1}) is estimated as the un-reflected proportion of daily shortwave radiation (SRAD, W m^{-2} day^{-1}), as computed by multiplying Rn and stand albedo (ALBEDO) (Gay 1979). The photon flux density (umol m^{-2} sec^{-1}) is computed from SRAD by multiplying it by two factors: the radiation to photosynthetically active radiation (PAR) ratio (0.45 in the model) and a conversion factor to convert radiation to umol m^{-2} sec^{-1} (4.55 in the model).

Daylength (D_l, sec) for a flat surface is computed from the equation:

$$D_l = 3060(\propto \sin(0.01721\ (YD - 79) + 12) \quad (16)$$

where YD is yearday (Julian date), and α is the amplitude of the diurnal day length sine function estimated from:

$$\propto = \frac{e^{(7.42 + 0.45LAT)}}{3600} \quad (17)$$

where LAT is the latitude of the site in decimal degrees, as specified in the Site.in file. Daylength is available from *MT-CLIM* output, but it is now computed within FireBGCv2 to save memory.

Weather-Related Variables

There are many other ecological weather attributes estimated from the raw weather data that are used in algorithms throughout the model. FireBGCv2 estimates the latest spring frost as the last day before the middle of the growing season (GS_{mid}, Julian date) with a minimum air temperature (T_{min}) below -3 °C. The middle of the growing season is currently Julian day 200 in FireBGCv2. The earliest fall frost is computed in a similar manner where the earliest autumnal frost after the middle of the growing season is recorded. These parameters are used in the Tree Regeneration algorithms. A number of FireBGCv2 routines use days since last rain (DSR) and days since last snow (DSS), which are computed as the number of days since at least 0.05 cm precipitation (Rainfall>Effective Precipitation or EPPT).

There are some precipitation-related variables computed in FireBGCv2 that are fed to *BGC* and mechanistic gap simulations. First, and most importantly, FireBGCv2 converts all precipitation variables from cm to kgW m^{-2} to be compatible with *BGC* routines (conversion factor is 0.1). Next, snow (SnowW, kgW m^{-2}) is simulated if the average temperature (T_{ave}) is less than 1 °C. EPPT (kgW m^{-2}) is rainfall that makes it to the forest floor and is calculated from the product of the interception coefficient (kgW m^{-2} LAI^{-1}, specified in the Species.in input file) and the projected leaf area index (PLAI, m^2 m^{-2}) of the stand. This value is the rainfall that is intercepted by the canopy (RainInterceptedW, kgW m^{-2}). If PPT is greater than RainInterceptedW, the difference is the amount of water that hits the forest floor (RainThrufallW, kgW m^{-2}), called EPPT in the model (kgW m^{-2}).

There are a couple of important fire-related weather variables that are computed each day. First, the KBDI is computed using the algorithms taken from Keetch and Byram (1968) and Burgan (1993). In FireBGCv2, KBDI is computed based on precipitation and temperature. If there is significant rainfall (above the interception coefficient) on a day, and that rainfall is above 0.5 cm or there was rain on the previous day, the KDBI is updated using this relationship:

$$KBDI_t = KBDI_{t-1} - (0.0005 + 100\text{NETPPT}) \quad (18)$$

where $KBDI_{t-1}$ is yesterday's KBDI, and NETPPT is the net precipitation (inches) as computed from the previous and current day's rainfall (inches). In addition, a heat sum (DQ) is estimated if the maximum temperature for the day is greater than 10 °C:

$$DQ = 0.001(800 - KBDI_{t-1})\left[\frac{(0.9676e^{0.0486T_{max})} - 8.299}{(1 + (10.88e^{-0.0441AAPPT}))}\right] \quad (19)$$

where T_{max} is the maximum temperature for that day converted to ^{o}F, and AAPPT is the average annual precipitation (converted to inches) as computed at the start of the simulation based on the weather file for that site. The complete KBDI algorithm is presented in Keetch and Byram (1968). The KBDI is initialized at 100 at the beginning of a FireBGCv2 simulation. FireBGCv2 also contains the algorithms to compute all fire danger indices (for example, energy release component, burning index, and spread component), but this has been disabled during simulation to decrease simulation times.

Phenology

The phenology of each species in the Species.in file is calculated at the site level for each year of simulation. Phenology simulations are used to increment litterfall and leaf growth for all trees and undergrowth on the simulation plot at a daily time step. The *BGC* simulations can use one of two phenology simulations–phenology can be simulated from hardwired Julian dates specified by species in the Species.in input file, or phenology can be modeled using the algorithms of White and others (1997). A detailed description of these phenology routines is presented in White and others (1997), so the routines won't be discussed here except in the modification to simulate phenology for the mechanistic gap model. The simple gap model implemented in FireBGCv2 does not simulate daily phenology because it models litterfall and leaf growth at an annual time step.

The phenology algorithms for the FireBGCv2 mechanistic gap model taken from White and others (1997) have some major adjustments by lifeform and species. There are four stages of phenology simulated for all lifeforms (evergreen conifer and deciduous broadleaf, for example) in FireBGCv2: (1) *dormant*, (2) *leaf out*, (3) *growing season*, and (4) *leaf fall*. The model starts all species in the *dormant* phase and simulates the transition to the next phases using Julian date and intermediate weather variables by major lifeform. This simulation is at a daily time step, so that on any day, the model knows the current phenological stage and grows or sheds foliage accordingly.

Conifers and Shrubs

All evergreen and deciduous conifers and shrubs are initialized as *dormant* at the beginning of a simulation. Litterfall for evergreen conifers is simulated evenly across all days as a proportion of the annual leaf fall (leafC divided by the leaf retention time, as specified by species in the Species.in file) divided by 365. Leaf growth initiation is simulated using the White and others (1997) equations where each day the program calculates a soil temperature summation (SOIL_TEMP_SUM) by summing positive soil temperatures for all days up to the seventh day after the day in question. It then compares the SOIL_TEMP_SUM to a tree green up onset date (TGOD) sum, as calculated at the beginning of a FireBGCv2 simulation for each site from the following relationship:

$$TGOD = e^{[4.795 + (0.129T_{aaave})]} \quad (20)$$

where T_{aaave} is average annual daily average temperature (^{o}C), which is calculated and stored by site at the very beginning of a FireBGCv2 simulation. If SOIL_TEMP_SUM greater than TGOD and JD is less than 182 (a date used to ensure green up occurs before July 1), then the phenological state of the evergreen transitions from the *dormant* stage to the *leaf out* stage.

Leaf out is simulated for the number of days specified for each species in the Species.in file, where it is called the species leaf period (assumed to be 14 in past *FIRE-BGC* simulations). During this time, new leaf material is added to each

conifer tree based on a maximum (described in the "Tree Processes" section). At the end of the *leaf out* stage (number of days in *leaf out* period>species leaf period), the model transitions the phenological stage to the *growing season* stage.

Growing season continues until day length is shorter than 39,300 seconds and the soil temperature (T_{soil}) is less than an average summer soil temperature (T_{sst}), as computed at the beginning of the simulation by taking an average across all years in the weather record of soil temperature between the Julian dates of 244 and 305. There is a logic check in the program for some rare weather years so that if the above mentioned conditions don't occur, *growing season* stops when soil temperature is less than 2 ^{o}C and Julian date is greater than 182. The species then transitions to the *leaf fall* phase, which is simulated exactly like the *leaf out* phase where the phase lasts for the input leaf period for the species. After the end of the leaf period, the species transitions to dormancy and stays that way until the next year when *leaf out* occurs.

Herbaceous Species

Grass and forb species' phenology are also simulated using the White and others (1997) algorithms. Herbaceous species are in the *dormant* phase until two critical criteria are met: first, the soil temperature summation (SOIL_TEMP_SUM) must be greater than a critical threshold ($HERB_{TEMP\_GREENUP}$) that is computed from:

$$HERB_{TEMP\_GREENUP} = 900 + (0.5 * (1380 - 418)) \frac{e^{[32.9(Taaave - 9.0)] - 1}}{e^{[32.9(Taaave - 9.0)] + 1}} \quad (21)$$

where T_{aaave} is average annual daily average temperature (^{o}C). Second, a precipitation sum (PPT_SUM) must be greater than a critical threshold (HERB_PPT_GREENUP). The precipitation sum is computed as the amount of precipitation accumulated from the first of the year (YD = 1), and the $HERB_{PPT\_GREENUP}$ threshold is computed as 15 percent of the average annual precipitation (m) across all weather years. If these criteria are met, the herb species transitions to the *leaf out* phase. Both the *leaf out and leaf fall* stages are simulated the same as evergreen conifers using the static number of days in the leaf period (input in Species.in file). At the end of the leaf period, the species transitions to the *growing season* phase.

Growing season for herbs lasts until the following criteria are met. First, the number of days in this stage has to be greater than 30. Then, the amount of precipitation in the previous 31 days has to be greater than 0.0114 m. Then, the amount of precipitation in the subsequent seven days has to be more than 0.0097 m. And last, the maximum temperature has to be greater than 92 percent of a site maximum that is computed as the maximum T_{max} over the entire weather record (computed at the beginning of the simulation). As a logic check for cold-canceling weather events, the herb species will also transition to the *leaf fall* stage when the three-day mean T_{min} is less than the average annual T_{min} for the site over all weather years and the Julian date is greater than 182. *Leaf fall* lasts for the input leaf period and then transitions to *dormancy* for the rest of the year and the beginning of the following year.

Wildland Fire

Fuels

The only fuel properties that are not static at the site level are fuel loadings and moistures. Loadings (kgB m^{-2}) for the eight dead fuel components (see Table 2) are computed from the forest floor carbon pools by dividing the carbon mass by the fraction of carbon to biomass (FCB, kgC kgB^{-1}) and the simulation plot area (PAREA, m^2) (see the "Stand Processes" section). The moisture contents of the fuel components are simulated at the stand level, but when a fire occurs, the wildfire fuel moisture conditions specified in the Fuel.in file (see "Fuel Moisture" in

the "Stand Processes" section) are used to simulate fire behavior and fire effects. Wind speed is another dynamic variable that is treated as static in FireBGCv2. Future versions of FireBGCv2 will incorporate mechanistic simulations of fuel moistures for fire behavior inputs.

All fuel properties, except moisture and loading, are specified in the Fuel.in input file as fuel models. The user can create several fuel models for the simulation area depending on vegetation and fuel characteristics. We used the fuel model parameters from Anderson (1982) to build a set of fuel models that we thought best represented the fuel conditions of the Glacier National Park simulation landscape (we used only 5 to 6 of Anderson's original 13). Values from both Anderson (1982) and Scott and Burgan (2005) can be used to build fuel models in the Fuel.in file.

Stand Processes

Vegetation Development

As mentioned, FireBGCv2 has three routines for simulating the process of succession or vegetation development, and the desired routine is specified in the Sim.in input file. The first option is a simple gap model taken directly from the *FIRESUM* model (Keane and others 1989, Keane and others 1990c). In this submodel, a maximum growth rate is reduced using reduction factors that represent light, stand density (nutrients), available water, and growing season temperature. This gap model is explained in detail in the Keane and others (1989) model documentation and, therefore, is not detailed here. The advantages of using this simple gap model are that it is quick, efficient, and highly generalized; however, there is a substantial loss of environmental feedbacks when using this simple gap approach. The primary disadvantage is that a simple gap model does not have the rich diversity of simulation output that is available with the other two submodels. This model does not simulate the flow of water, nitrogen, and carbon across stand carbon pools. As a result, several important ecological processes and their interactions are not represented in the simulation, such as the effect of moisture and temperature on fuel decomposition, the flow of carbon from plant respiration to the atmosphere, and the direct influence of climate on tree growth.

The most complex and detailed simulation of ecosystem dynamics occurs when the user selects the *BGC* simulation option for plant growth. The *BGC* algorithms are thoroughly documented in a number of papers (Running and Hunt 1993, Thornton and White 1996, White and others 2000, Thornton and others 2002) and on the website http://www.ntsg.umt.edu/models/bgc. The *BGC* submodel uses the routines from the big-leaf, ecosystem model *BIOME-BGC* (Running and Hunt 1993, White and others 2000, Thornton and others 2002). The first version of FireBGCv2 (*FIRE-BGC*) incorporated an early version of *BIOME-BGC* that was developed by Running and Coughlan (1988) and Running and others (1989). In the 1990s, a complete model revision occurred that was started by Running and Hunt (1993) and completed by Thornton (1998), White and others (2000), and Thornton and others (2002). The new *BIOME-BGC* model has since been implemented in its entirety into the FireBGCv2 code (Figure 1). When a *BGC* simulation is selected, a complex and extensive daily simulation of a number of ecosystem processes is initiated, including carbon, nitrogen, and water flux across a number of ecosystem components (leaf, stem, and root compartments). This simulation is quite demanding and takes a great deal of simulation resources such as memory and computation time. In return, a rich collection of interacting variables are available as output to explore ecosystem functions and response. One major problem with the *BGC* simulation is that it is difficult to scale the carbon allocated to the stand's leaf, stem, and root compartments and then allocate them to the tree's leaf, stem, and root compartments. The *FIRE-BGC* version used

leaf area and shade tolerance to perform this allocation, but many small trees in the understory were given insufficient carbon, especially shade-intolerant species (Keane and others 1996b). The new FireBGCv2 improves on this by allocating carbon by an annual carbon sum.

The last option is the mechanistic gap model simulation of ecosystem dynamics. This option was designed to be a compromise between the overly simplistic gap model and the computationally extensive *BGC* simulation (Figure 10). This option provides the full simulation of carbon and water in an ecosystem but still uses growth reduction factors to drive tree and undergrowth growth, and these scalars are now linked to the simulated ecosystem processes. This option does not include a cycling of nitrogen in the design, but it does simulate all other ecosystem biophysical processes at the same level of detail as the mechanistic *BGC* submodel because most of the algorithms are based on *BGC* design. The mechanistic gap model is the only option that is discussed in detail in this report.

Mechanistic Gap Biophysical Simulation

The mechanistic ecosystem process gap submodel for simulating plant dynamics uses many of the *BGC* environmental algorithms along with various additional biophysical relationships to simulate tree and undergrowth growth using a highly mechanistic gap approach (Figure 3). This gap model does not have the problems associated with the *BGC* simulation (inability to consistently allocate sufficient carbon to tree growth), yet still simulates the flow of carbon and water throughout the stand.

A mechanistic approach to simulating forest growth involves the complex simulation of all the ecological processes that drive growth for that ecosystem. This mechanistic simulation effort starts with the calculation of soil water potential (Ψ, also termed PSI, Pa) that describes the pressure (tension) needed to extract water from the soil matrix. In FireBGCv2, soil water potential (Ψ, Pa) is computed with the following relationship developed by Cosby and others (1984):

$$\psi = \psi_{sat}\left(\frac{VMC}{VMC_{sat}}\right)^{b} \tag{22}$$

where Ψ_{sat} (Pa) is the soil water potential at soil saturation, VMC_{sat} is the soil volumetric water content (percent) at saturation, VMC is the soil water content for the day in question (percent), and b is an empirical parameter. All of these variables are parameters that are estimated from the following equations using percent sand (SAND, %), silt (SILT, %), and clay (CLAY, %) for the free rooting zone for a site:

$$b = -(3.1 + 0.157CLAY - 0.003SAND) \tag{23}$$

$$VMC_{sat} = \frac{50.5 - 0.142SAND - 0.037CLAY}{100} \tag{24}$$

$$\Psi_{sat} = -0.000098e^{[(1.54-0.0095SAND + 0.0063SILT)\log(10)]} \tag{25}$$

$$VMC_{fc} = VMC_{sat}\left[\frac{-0.015}{\psi_{sat}}\right]^{(1/b)} \tag{26}$$

where VMC_{fc} is the soil volumetric water content at field capacity, as defined by Crosby and others (1986). VMC is the soil volumetric water content of a stand for a particular day (percent), and it is estimated from the amount of available soil water (SoilW, kgW m^{-2}) in the soil profile using the following relationship:

$$VMC = \frac{SoilW}{1000(SOILDEPTH)} \quad (27)$$

where SOILDEPTH (m) is the depth of the free rooting zone, as specified for each site.

The available soil water (SoilW, kgW m^{-2}) is computed from a water balance algorithm that attempts to balance the processes that utilize water (transpiration, evaporation, and runoff) with processes that fill the soil profile with water (precipitation and outflow). This algorithm first adds effective precipitation (EPPT, kgW m^{-2}) to the soil water (SoilW, kgW m^{-2}). If the new computed VMC exceeds the amount that the soil profile can hold (VMC_{fc}), then the excess is shunted to runoff (OutflowW, kgW m^{-2}). The model then computes estimates of actual evapotranspiration (AET, kgW m^{-2}) and evaporation (EVAP, kgW m^{-2}) using the Penmon equation presented in the middle of this section. The daily AET is subtracted from the soil water (SoilW) and the soil moisture properties (VMC, Ψ) are recalculated. FireBGCv2 assumes there is no water flow from stand to stand.

Estimates of conductances—*g* (the inverse of resistance or 1 / r_v)—are needed for computing evapotranspiration (ET, kgW m^{-2}). This is accomplished by reducing a maximum conductance (g_{max}, kgW sec^{-1}), as specified by species in the Species.in file and summarized to the stand level by the leaf area weighed average, by several scalars that account for environmental interactions using the following equation:

$$g_l = g_{max}\left(\frac{1}{r_c}\right)(r\text{TEMP})(\text{rVPD})(\text{rSWP})(\text{rPPFD}) \quad (28)$$

where g_l is the leaf-level conductance (sec), and r_c is the correction factor for temperature and pressure as follows:

$$r_c = \frac{1}{\left[\frac{101300}{AP}\right]\left[\frac{(T_{day}+273.15)}{293.15}\right]^{1.75}} \quad (29)$$

where T_{day} is daytime temperature (°C), and AP is atmospheric pressure (MPa). The rest of the terms are reduction factors that are computed from the following relationships using previously described variables. All reduction scalars (rTEMP, rVPD, rSWP, rPPFD) are bounded to the range 0.0 to 1.0 (Thornton 1998, White and others 1998, White and others 2000). The scalar that accounts for stand temperature (rTEMP) is calculated from:

$$rTEMP = 1 + 0.125T_{min} \quad (30)$$

where T_{min} (°C) is the daily minimum temperature. The reduction factor that accounts for the vapor pressure deficit (humidity) influences on stomatal conductance is:

$$rVPD = \frac{(VPD_{close} - VPD)}{(VPD_{close} - VPD_{open})} \quad (31)$$

where VPD_{close} and VPD_{open} are the vapor pressure deficits (Pa) for closing and opening stomata, as specified by species in the Species.in file and summarized for the canopy based on a leaf area weighted average (see the "Canopy Dynamics" section). The daily VPD is taken from the *MT-CLIM* input file as part of the weather stream. The scalar to account for soil water potential effects on conductance (rSWP) is similar to that for VPD:

$$rSWP = \frac{(\psi_{close} - \psi)}{(\psi_{close} - \psi_{open})} \quad (32)$$

where Ψ_{close} and Ψ_{open} are the soil water potential (MPa) for stomatal closing and opening, and Ψ is the daily soil water potential (MPa). The scalar that represents

light effects on stomatal opening (rPPFD) is calculated using the following equation:

$$rPPFD = \frac{PPFD_{plai}}{PPFD_{plai} + PPFD_{50}} \quad (33)$$

$PPFD_{50}$ is the PAR (photosynthetically active radiation) photon flux density (umol sec^{-1}) needed to open 50 percent of the stomata, and it is hardwired into the program as 75.0 umol m^{-2} sec^{-1} (Thornton and others 2002). $PPFD_{plai}$ is the PAR photon flux density per unit of projected leaf area index and it is computed from the following relationship:

$$PPFD_{plai} = k(PAR)(1 - \frac{ALBEDO}{3})E \quad (34)$$

where k is the extinction coefficient specified by species in the Species.in file, ALBEDO is the stand albedo that is dynamically modeled using relationships presented in this section, and PAR is radiation flux only in the photosynthetically active range (PAR, 400 to 700 nm). E is a factor to convert PAR radiation flux (kW m^{-2}) to PAR photon flux density (umol m^{-2} sec^{-1}) (assigned as 4.55 in FireBGCv2).

These conductances are computed for both sunlit and shaded leaves using a variation of the rPPFD scalar where the proportion of photon flux density to the shaded leaves (rSHADE) is computed from the equation:

$$rSHADE = 1 - e^{-kPLAI} \quad (35)$$

where k is the extinction coefficient and PLAI is the projected leaf area index (m^2 m^{-2}). So, the proportion of flux density to sunlit leaves is 1 - rSHADE. The proportion of sunlit leaves in the canopy is calculated from the ratio of sun to shade leaves, as specified in the Species.in file according to species.

Each day, the program computes three leaf area measures at the stand level that are used throughout the program and described in the "Canopy Dynamics" section: LAI (all-sided leaf area index), and the PLAI (projected leaf area index) of the sunlit and shaded leaves. The program calculates the PLAI of sunlit leaves (PLAISUN) by multiplying PLAI with ($1-e^{-PLAI}$), and then PLAISHADE (shaded projected leaf area index) is PLAI - PLAISUN. These three major canopy state variables change throughout the year as phenological events occur to both the undergrowth and trees.

Stand albedo (ALBEDO) is simulated at the stand level to account for the role of vegetation in light dynamics. Each day, the program evaluates stand albedo by first assigning a default albedo to the stand, as taken from an input in the Site.in file. However, this default pertains only to evergreen coniferous canopies, and the program changes albedo to 0.18 if the lifeform of the stand is deciduous, 0.2 if the stand is shrub-dominated, and 0.25 if the stand is grass-dominated. Next, the program checks to see if the stand has a snowpack (SnowW > 0.05 kgW m^{-2}); if there is a snowpack, a second snow albedo (SALBEDO) is computed from the following equation:

$$SALBEDO = 0.88 - (SDECAY)(STDA) \quad (36)$$

where SDECAY is the snow albedo decay coefficient assigned as 0.004 in FireBGCv2 (White and others 1998), and STDA is the snowpack temperature deficit (^oC) that is calculated as the summation of daytime temperature (T_{day}) when there is snow on the ground (minimum value of -5 ^oC). Then, if the projected leaf area index (PLAI) is below 1.0 m^2 m^{-2}, albedo is assigned the SALBEDO value; but if PLAI is greater than 1.0, then ALBEDO is calculated as the average of the default albedo and SALBEDO.

Three estimates of conductance (g) are computed within the mechanistic gap module of FireBGCv2. The leaf-level conductance (g_l) is computed as the g value in the previous equations. The leaf-level conductance to sensible heat (g_{lsh}) is computed as the product of the boundary-level conductance (assigned in the Species.in file) and the correction factor ($1 / r_c$), as computed in the previous equations. The canopy-level conductance to sensible heat (g_{csh}) is computed by multiplying g_{lsh} with PLAI.

There are a number of biophysical variables computed in FireBGCv2 at the stand level that depend on some form of the Penmon-Monteith equation (Monteith 1973) calculated at a daily time step:

$$ET = \frac{[\Delta SRAD + \frac{(c_p p_a) VPD}{r_{hr}}]}{[\Delta + (\frac{a_p c_p r_v}{\lambda r_{hr} b})]} \tag{37}$$

where ET is evapotranspiration (kgW m^{-2}), c_p is specific heat of air (1010.0 J kgW K^{-1}), p_a is air density estimated from $p_a = 1.292 - (0.00428T_{day})$, λ is the latent heat of vaporization estimated by $\lambda = 2.5023x10^{-6} - (2430.54T_{day})$, b is a unitless ratio of molecular weights (0.6219) for water in the atmosphere, and Δ is the slope of the vapor pressure deficit curve estimated from the following relationship:

$$\Delta = \frac{(610.78_{e^{[\frac{17.38T_1}{239+T_1}]}} - 610.78_{e^{[\frac{17.38T_2}{239+T_2}]}}}{(T_1 - T_2)} \tag{38}$$

where $T_1 = T_{day} + 0.2$ and $T_2 = T_{day} - 0.2$. The term a_p (Pa) is atmospheric pressure estimated from:

$$a_p = 101325[1 - (0.0065 ELEV / 288.15)]^{[\frac{GS}{LR(RR/MA)}]} \tag{39}$$

where ELEV is the stand elevation (m), GS is standard gravitational acceleration (9.80665 m sec^{-1}), LR is standard temperature lapse rate (0.0065 –K m^{-1}), RR is the gas law constant (8.3143 m^3 Pa mol^{-1} K^{-1}), and MA is the molecular weight of air (kg mol^{-1}) (Iribane and Godson 1981, Thornton and Running 1999).
The resistance terms in this equation are:

$$r_{hr} = \frac{r_r r_h}{(r_r + r_h)} \tag{40}$$

where r_r is estimated from the Stefan-Boltzmann constant ν ($5.67x10^{-8}$, W [m^2 $^oK^4$]$^{-1}$) and T_k (T_{day} + 273, ^oK) using the following relationship:

$$r_r = \frac{p_a c_p}{(4 \upsilon T_k^3)} \tag{41}$$

In calculating potential evapotranspiration (PET, kgW m^{-2}), the terms r_h (resistance to sensible heat, m^{-1}) and r_v (resistance to latent heat, m^{-1}) are set equal to boundary layer resistance (r_b sec m^{-1}) as estimated from the following equation:

$$r_b = 107 r_c \tag{42}$$

In calculating actual evapotranspiration (AET, kgW m^{-2}), the terms r_h and r_v must be estimated from the dynamic simulation of water flux from precipitation to the soil profile and then to the plants in the stand. The resistances (r) are converted to conductances (g) in the final output for ease of computation by simply taking the inverse ($g = 1 / r$).

To calculate bare soil evaporation (EVAP, kgW m^{-2}), the PET is calculated, and then reduced based on precipitation and days since precipitation. If the effective precipitation (EPPT, kgW m^{-2}) is greater than PET, then EVAP is set at 60 percent

of PET. If EPPT is less than PET, then the days since last rainfall (DSR) is used to calculate an alternative ratio:

$$ER = \frac{0.3}{DSR^2}, then\ EVAP = (ER)(PET) \quad (43)$$

where ER is the evaporation ratio (dimensionless) if there is no significant rainfall.

Radiation computations are quite important in FireBGCv2, and they are calculated from the net daily canopy shortwave radiation (SRAD, W m^{-2} day^{-1}) that is input to FireBGCv2 and is often derived using the *MT-CLIM* program. A daily estimate of photosynthetically active radiation (PAR) is calculated by multiplying SRAD by 0.45. Next, the shortwave reflected radiation (SWREF) is computed by multiplying SRAD by stand albedo (ALBEDO). Stand shortwave radiation (SW) is calculated as the difference between SRAD and SWREF, and the absorbed shortwave radiation (SWABS) is calculated from SW using the following:

$$SWABS = SW(1 - e^{-kPLAI}) \quad (44)$$

where *k* is the extinction coefficient estimated each year using the weighted average of leaf area across all species' extinction coefficients (see the "Canopy Dynamics" section), and PLAI is the projected leaf area index (m^2 m^{-2}). Transmitted shortwave radiation (SWTRANS) is the difference between SW and SWABS (SW - SWABS).

Snowfall dynamics are computed from algorithms taken directly from *BIOME-BGC* (Thornton 1998) and *FIRE-BGC* (Keane and others 1996b), where precipitation that falls when daytime temperature (T_{day}) is below freezing (0 ºC) is considered snow. Snow melts as a function of temperature, radiation, and vapor pressure deficit. Snowpack (SnowW) is reduced by five factors (temperature, condensation, rain, radiation, and sublimation) when T_{ave} is above freezing using the following empirical functions found in Thornton (1998). Temperature-induced snowmelt (TMELT, kgW m^{-2}) is computed by multiplying the daily average temperature (T_{ave}) by a snowmelt coefficient (0.65 kgW m^{-2} $^oC^{-1}$ day^{-1}). The condensation melt (CMELT) is computed from the following equation:

$$CMELT = 0.0000078(230)\,\beta\,[(0.42T_{day}) - (1.51T_{min})] \quad (45)$$

where ß is the conversion from cm to kgW and T_{min} is minimum daily temperature (ºC). Snowmelt from rainfall (RMELT, kgW) is computed from the following:

$$RMELT = 0.00012\,\beta\,EPPT(T_{day}) \quad (46)$$

And the melt from the radiation load (RADMELT, kgW) is computed from SRAD / LHFUS where LHFUS is the latent heat of fusion (335 kj kgW^{-1}). Sublimation only occurs when T_{ave} is below freezing and it is estimated the same way as RADMELT. These losses are summed and the total loss is taken from the snowpack (SnowW).

Autotrophic respiration is also simulated at the daily time step using identical simulation methods as in *BGC*. Respiration (kgC) is computed using the general formula:

$$MR = A1(Q10^{A2}) \quad (47)$$

where MR is maintenance respiration (kgC), Q10 is set at 2.0, and coefficients A1 and A2 are calculated based on the tree or stand carbon compartment and time of day. For leaf daytime respiration, the following equations are used for A1 and A2:

$$A1 = (MRP)\frac{LeafC}{LeafCN} \quad (48)$$

$$A2 = \frac{(T_{day} - 20)}{10} \quad (49)$$

where MRP is a maintenance respiration coefficient that accounts for carbon and nitrogen (0.218 kgC kgN^{-1} day^{-1}), LeafC is the mass of carbon in leaves, T_{day} is the daytime temperature (^oC), and LeafCN is the leaf carbon to nitrogen ratio, as specified in the Species.in file. Nighttime leaf respiration is calculated by substituting T_{night} for T_{day} to calculate A2, while fine and coarse root respiration are calculated using T_{soil}, the fine and coarse root carbon:nitrogen ratio (FrootCN and CrootCN), and the amount of fine and coarse root carbon (FrootC and CrootC). Live stem carbon respiration is computed using T_{ave}, StemCN, and LivestemC. Daytime leaf respiration is divided into sun and shade leaves and then converted to a rate per second using daylength for input into the photosynthesis computation.

Gross canopy photosynthesis (PSN, kg CO_2 day^{-1}) is computed from the Farquhar and others (1980) algorithm, as implemented in the *BGC* module. This routine is quite complicated and is discussed in detail in von Caemmerer (2000). This routine uses the following input variables that are computed daily for both sunlit and shaded leaves:

- T_{day} (^oC). Daytime temperature.
- Photosynthetic pathway (C3 or C4). Set as C3 for most plants in FireBGCv2, but this will be dynamic in future versions.
- ACO2 (ppm). Concentration of carbon dioxide in the atmosphere, as specified in the Climate.in file and modified in the weather routines.
- LNC (kgN m^{-2}). Leaf nitrogen concentration per unit projected leaf area is calculated as 1 / [(PSLA)(LeafCN)] where PSLA is the projected specific leaf area.
- FLNR (proportion). Fraction of leafN in Rubisco (input in Species.in file).
- PPFD (umol m^{-2} sec^{-1}). Photon flux density of sun/shade leaves, as previously computed.
- DLMR. Daytime respiration of sun/shade leaves per projected leaf area.
- g_l (sec^{-1}). Leaf conductance, as previously computed.

The Farquhar algorithm outputs a photosynthetic flux density per unit leaf area that is then converted to kgC day^{-1} based on daylength (sec) and leaf area index.

BGC Simulation

As mentioned earlier, all *BGC* algorithms are discussed in other documents. However, there are some important *BGC*-based simulations, performed at the stand level and used to allocate carbon from the stand level to the tree level, that merit additional description. FireBGCv2 uses *BGC* algorithms to estimate daily respiration (MR, kgC) and photosynthesis (PSN, kgC). The PSN and MR variables are then summed for each tree across all days in the year and the radiation input is adjusted by multiplying SRAD by the proportion of available light at the top of the canopy (AL), as described in the "Canopy Dynamics" section. Next, all stand-level *BGC* input parameters are replaced by the species-level parameters defined in the FireBGCv2 Species.in input file. Radiation transfer, as summarized in the "Mechanistic Gap Biophysical Simulation" and "Weather" sections, is then recomputed for each tree using tree-level parameters and available light at the top of each tree or undergrowth guild.

Undergrowth Dynamics

Most big-leaf models, such as *FOREST-BGC*, and some gap models, such as *JABOWA* (Botkin 1993), ignore undergrowth growth dynamics and interactions with other ecosystem processes. However, undergrowth dynamics are important in many ecosystems, especially rangeland, alpine, and early successional communities (Kelliher and others 1986). Undergrowth plants contain important carbon stocks, contribute to ecosystem productivity, and comprise the majority of fine fuels for most fuel beds. Their influence on tree regeneration and light distribution is included in FireBGCv2, along with their interactions with water, light, fire ignition, and fire spread. As mentioned in the "Undergrowth Dynamics" section in "Model Design," the undergrowth is modeled in FireBGCv2 using suites of species called plant guilds, which are individually parameterized using plant models that are then assigned to sites. Guilds are analogous to plant functional types that are collections of species grouped by their functional roles in stand dynamics. The design and number of plant guilds in a simulation depends on the modeling objective and available data.

Growth in biomass of the undergrowth guild compartments (Figure 8) is computed using a deterministic method that estimates the maximum growth in biomass (kgB) of individual undergrowth compartment (UBIOMASS) and then reduces this maximum by reduction factors (Keane and others 1990c, Kercher and Axelrod 1984). The computation of the growth (UGROWTH, kgB m^{-2}) uses the following equation:

$$UGROWTH = (rSHADE)(n)(UBIOMASS_{t-1})(1 - \frac{UBIOMASS_{t-1}}{UBIOMASS_{\max}}) \quad (50)$$

where $UBIOMASS_{t-1}$ is the previous year's biomass of the undergrowth compartment (kgB m^{-2}), n is a growth constant for the undergrowth compartment ($year^{-1}$), and $UBIOMASS_{max}$ is the maximum attainable biomass for the compartment (kgB m^{-2}). In previous studies, values for n_i were estimated at 1.441 $year^{-1}$ for shrubs (Keane and others 1996b) and 10.842 $year^{-1}$ for herbaceous fuel from field data. $UBIOMASS_{max}$ values can be estimated from field studies as the maximum loading of a suite of species across all field plots used in parameterization (specified in Plant.in file). The light reduction scalar rSHADE (dimensionless) is calculated from a set of relationships based on shade tolerance of the undergrowth component, as specified by species in the Plant.in input file and taken from the Species.in file. This scalar uses the shade tolerance index of a species to key to one of these equations:

$$rSHADE = e^{-1.2PLAI} \text{ for very shade intolerant species } (index = 1) \quad (51)$$

$$rSHADE = e^{-0.4PLAI} \text{ for shade intolerant species } (index = 2) \quad (52)$$

$$rSHADE = e^{-0.25PLAI} \text{ for moderately shade tolerant species } (index = 3) \quad (53)$$

$$rSHADE = e^{-0.15PLAI} \text{ for shade tolerant species } (index = 4) \quad (54)$$

$$rSHADE = e^{-0.05PLAI} \text{ for very shade tolerant species } (index = 5) \quad (55)$$

where PLAI is stand projected leaf area index ($m^2\ m^{-2}$) for all trees and undergrowth above the undergrowth component (Figure 6). The new growth in UGROWTH (kgB m^{-2}) is added onto last year's biomass (UGROWTH + UBIOMASS) to get the current year's biomass estimates. This growth can be negative or positive and only occurs during the growing season.

The change in an undergrowth guild's height (UHT, m) is simulated using the same relationships as above, except the height parameters are substituted for the biomass parameters. The maximum height (UHT_{max}) is taken from the plant

model assigned to that site. The growth rate (*n*) and the rSHADE are the same as above. This height can slide up or down depending on the amount of light at the top of the undergrowth canopy.

Phenology, and its influence on component biomass throughout the growing season and remaining part of the year, is a final key component of the simulation of understory dynamics. Undergrowth phenology is simulated at the site level using the value for the current year UBIOMASS (UGROWTH + $UBIOMASS_{t-1}$) as the biomass at the height of the growing season, adjusted by the fraction of undergrowth biomass dead at time of fire (FRAC). The FRAC value increases biomass during the *leaf out* phenological stage and reduces biomass during the *leaf fall* stage.

Ground Dynamics

The method used to calculate decomposition dynamics in FireBGCv2 is based on the *BGC* approach where forest floor respiration is influenced by climate, particle size, and vegetation inputs (Figure 3). The original *FOREST-BGC* and the new *BGC* decomposition routines did not provide the detail needed to simulate wildland fire process interactions because compartments representing the forest floor were not stratified by fuel size class. Therefore, FireBGCv2 was refined to stratify the forest floor into eight compartments to predict fire behavior and effects (Figure 4, Table 2).

As previously mentioned, organic matter on the forest floor is represented in FireBGCv2 as carbon pools that are contained within eight compartments (Table 2). These compartments are quantified by the loading (amount of carbon, kgC m^{-2}) by fuel classes on the forest floor. The soil (SoilC, kgC m^{-2}) and duff (DuffC, kgC m^{-2}) carbon compartments are typically composed of mostly lignin-based, partially decomposed material from leaf and stem turnover. The leaf material falling to the ground (LeaffallC, kgC m^{-2}) and litter (LitterC, kgC m^{-2}) compartments contain freshly deposited carbon that is quickly decomposed and year-old leaf material that is not lignin, respectively. The four woody compartments (W1C, W10C, W100C, and W1000C; kgC m^{-2}) are defined by the average diameter or size of woody particle: twigs of 0 to 1 cm diameter, branches of 1 to 3 cm diameter, large branchwood of 3 to 7 cm diameter, and logs of 7+ cm diameter, respectively. These particle size classes correspond to standard woody fuel size classes used to predict fire behavior (1, 10, 100, and 1000 hr timelag woody fuel components) (Albini 1976, Fosberg 1970).

Organic Matter Accumulation

Accumulation of organic material on the forest floor is computed at both a daily and annual time step from stem, leaf, and root turnover of the simulated trees and undergrowth, depending on the succession driver module (simple gap, mechanistic gap, and *BGC*) (Figure 7). Each day, the model computes the amount of foliar litterfall based on the daily phenology described in the "Site Processes" section. This carbon is deposited into the LeaffallC ground compartment (kgC m^{-2}) on a daily level, and at the end of the year, this amount is equal to the stand-level LeafC divided by leaf retention time. Currently, the leaffall from evergreen conifer trees is evenly distributed over the entire year with the total amount being the total LeafC for the tree divided by the leaf retention time (LSPAN) parameterized by species in the Species.in file. Deciduous tree species lose all of their foliar carbon during the *leaf fall* phenological stage and gain it all back during the *leaf out* stage.

Undergrowth plant contributions to the LeaffallC are computed from biomass turnover also estimated at a daily time step from LSPAN (year) for the species assigned to the plant model (Plant.in file) and parameterized in the Species.in file. Undergrowth LeaffallC is computed from the following:

$$LeaffallC = LeaffallC + [\frac{(UBIOMASS)(LFRAC)(FLBC)}{LSPAN}] \quad (56)$$

where UBIOMASS is the biomass of an undergrowth component (kgB m^{-2}), LFRAC is the fraction of undergrowth biomass that is leaf (proportion), and FLBC is a constant that is the proportion of leaf biomass that is carbon (0.48 in FireBGCv2). Some twig, branch, and large branch wood are added to the woody carbon compartment at year's end:

$$W1C = W1C_{t\text{-}1}[(UBIOMASS)(1\text{-}LFRAC)(DWTF)] \quad (57)$$

where DWTF is the deadwood turnover fraction specified according to species in the Species.in file and referenced in the plant model file (Plant.in).

Decomposition

The decomposition routine detailed here only applies to the mechanistic gap model. If the *BGC* vegetation model is selected, the decomposition is done exactly the same as that described for *BIOME-BGC* by Thornton (1998). Decomposition for the simple gap model uses the following routines but at an annual, rather than a daily, time step, meaning that all weather parameters below are computed as averages across the year.

Decomposition from forest floor compartment carbon pools (Figure 3) is calculated as a function of the soil water and temperature. Each day, two scalars are calculated from the weather data and algorithms previously presented:

$$rSOILW = \frac{\ln[\frac{\psi_{\min}}{\psi}]}{\ln[\frac{\psi_{\min}}{\psi_{\max}}]} \quad (58)$$

$$rSOILT = e^{308.56[\left(\frac{1}{71.02}\right) - \frac{1}{(Tsoil + 273.15) - 227.13}]} \quad (59)$$

where rSOILW and rSOILT are the soil water and temperature scalars; Ψ_{min} and Ψ_{max} are the minimum and maximum soil water potentials for opening and closing stomata, as specified per species in the Species.in file and summarized for the canopy (see the "Canopy Dynamics" section); Ψ is the soil water potential (MPa) for that day; and T_{soil} is the soil temperature for that day. Both scalars are bounded between 0.0 and 1.0.

There are several fuel fragmentation factors built into FireBGCv2 that are based on the algorithms in *BGC* (Thornton and others 2002). A static base fragmentation factor (kFRAG, assumed to be 0.001) represents the physical breakage of woody fuels due to weathering and soil macrobiotic activity. There are also static scalars to account for the size of the fuel particles: sW1 (assigned a value of 0.7 in FireBGCv2), sW10 (assigned 0.5), sW100 (assigned 0.2), and sW1000 (assigned 0.01). Computation of all decomposition fluxes involves the multiplication of the soil scalars (rSOILW and rSOILT), the base fragmentation (kFRAG), and size scalars (sW1 to sW1000) with the amount of carbon in the ground component pools. For example, decomposition for twigs (W1C, kgC m^{-2}) is calculated as:

$$W1C_t = W1C_{t\text{-}1} - W1C_{t\text{-}1}\,(rSOILW)(rSOILT)(kFRAG)(sW1)(\frac{1}{TIME}) \quad 60)$$

where *t* is time (day or year) and TIME is the number of time steps in the year (365 for a daily time step).

Additions to the DuffC (kgC m^{-2}) ground component are computed by multiplying carbon loadings of the W1C, W10C, W100C, and W1000C by the four factors each day. The formula for losses to DuffC from the W1C pool is:

$$DuffC_t = DuffC_{t\text{-}1} + (W1C)(kFRAG)(sW1)(rSOILW)(rSOILT) \quad (61)$$

This formula is repeated for each woody fuel ground component, substituting the appropriate size scalars and fuel component carbon loadings.

There are also losses from the woody fuel components to the soil carbon pool (SoilC, kgC m^{-2}). These are calculated using the four scalars and an additional scalar that is stratified by the proportion of the carbon that is cellulose versus lignin. The formula for twigs (W1C) is:

$$SoilC_t = SoilC_{t\text{-}1} + [(KL2)(PCELL)(W1C) +$$

$$(LK4)(PLIG)(W1C)](kFRAG)(sW1)(rSOILW)(rSOILT) \quad (62)$$

where KL2 and KL4 are decomposition constants for the cellulose and lignin proportions of the wood (assigned 0.07 and 0.014, respectively, from Thornton and White [1996]), and PCELL and PLIG are the proportion of the wood that is cellulose and lignin, respectively, as specified in the Species.in file and summarized to the stand level using methods in the "Canopy Dynamics" section.

Fresh litterfall (LeaffallC, kgC m^{-2}) is transferred to the litter component (LitterC, kgC m^{-2}) based on the two soil scalars:

$$LitterC_t = LitterC_{t\text{-}1} + [(rSOILT)(rSOILW)(LeaffallC)] \quad (63)$$

where *t*-1 indicates the LitterC loading the previous day. Any material from the litter component is transferred to the duff (DuffC) based on the *BGC* decomposition scalar KL2:

$$DuffC_t = DuffC_{t\text{-}1} + [(KL2)(rSOILT)(rSOILW)(LitterC)] \quad (64)$$

Material from the duff is lost to the soil carbon (SoilC, kgC m^{-2}) based on another decomposition factor (KS3 = 0.0014):

$$SoilC_t = SoilC_{t\text{-}1} + [(KS3)(rSOILT)(rSOILW)(DuffC)] \quad (65)$$

These fluxes are summed each day to compute carbon losses from decomposition.

Nitrogen Cycling

There is no detailed nitrogen cycling for the simple and mechanistic gap models. In the *BGC* simulation, nitrogen is released from the forest floor compartments as a function of the fraction of carbon decomposed and a decomposition release factor (Running and Gower 1991). The nitrogen released by the decomposition process goes directly into the available nitrogen pool (AvailN, kgN m^{-2}) except for a portion that is lost from the simulation plot (Fahey 1983). The mobile nitrogen retention time represents the rate of leaching, volatilization, or some other loss of nitrogen from the system (Aber and others 1978; Aber and others 1991; Berg and Ekbohm 1993). Volatilization from fire is the only other means by which nitrogen can be lost from the stand (see the "Wildland Fire" section). The only external sources of nitrogen input are atmospheric deposition and biological fixation by plants or microbes, which are specified in the Climate.in file. Both parameters are assumed to be constants across simulation time.

Fuel Moisture

Fuel moisture for the downed woody fine fuel ground compartment (W1C) is simulated in FireBGCv2 using the same routines that are implemented in the FARSITE program (Finney 1996). In those routines, the wind (specified as a constant in the Site.in file), temperature, precipitation, relative humidity, and

at-the-ground radiation (attenuated through the canopy and adjusted for solar azimuth, zenith, and declination) are used to drive an equilibrium wetting and drying curve that is then used to compute an equilibrium fuel moisture content. Moisture content of the 1 hr woody fuels are also assigned to the litter fuels (LitterC).

Fuel moistures of the coarse woody fuel components (W10C, W100C, and W1000C) are computed using the algorithms from the National Fire Danger Rating System (NFDRS) (Deeming and others 1977). In NFDRS methods, temperature, humidity, and precipitation are used to compute equilibrium fuel moisture content (EMC). The EMC is then used to derive a moisture value for the W10C fuels based on empirical relationships. The W100C moisture content is based on the EMC and the amount and duration of precipitation. The log moisture content (W1000C) is estimated from a seven-day running average and the EMC. We assigned the log moisture content to the duff fuels (DuffC) for lack of a better method.

Live fuel moisture contents (MC_{foliar}) of the trees and undergrowth are simulated in FireBGCv2 from the soil water potential and two species-level parameters that are summarized for the canopy (Keane and others 2010). This algorithm scales foliar moisture content between a minimum and maximum using this relationship:

$$MC_{foliar} = FM_{max} - \left[(FM_{max} - FM_{min})(\frac{\psi_{close} - \psi}{\psi_{close} - \psi_{open}}) \right] \quad (66)$$

where FM_{max} and FM_{min} are the minimum and maximum foliar moisture contents (percent) for the landscape (hardwired in the model as 200 percent and 90 percent, respectively), Ψ_{close} and Ψ_{open} are the pre-dawn leaf water potentials for stomata closing and opening (MPa) (specified in the Species.in file and summarized for the canopy using a leaf area weighted average), and Ψ is the current soil water potential (MPa).

Canopy Dynamics

A major limitation of the big-leaf *FOREST-BGC* model is that species and canopy dynamics are not explicitly recognized in the model design (Running and Coughlan 1988, Friend and others 1997). Stand-level bioenvironmental processes are greatly influenced by canopy dynamics brought about by the changes in species composition and structure resulting from succession (Busing 1991, Dalla-Tea and Jokela 1991, Gilmore and others 1995, Choi and others 2001). FireBGCv2 improves the simulation of canopy dynamics over *FIRE-BGC*, *FIRESUM*, and *FOREST-BGC* by explicitly recognizing the vertical leaf area and available light distributions within the stand's canopy above the ground on the simulation plot. This allows a more accurate characterization of forest canopy influences on the coarser and finer scale processes simulated by FireBGCv2 such as radiation, water, and carbon fluxes.

The forest canopy in FireBGCv2 is represented by vertical layers above the ground on the simulation plot (Figure 11). FireBGCv2 "slices" the area above the simulation plot into vertically arranged canopy layers. The thickness of each canopy layer (HSIZE, m) and the number of layers (MXHGT) are defined in the Sim.in file. Three attributes are computed for each canopy layer—leaf area (LA, m^2), projected leaf area (PLA, m^2), and available light (AL, index 0 to 1). All canopy-related parameters used in the *BGC* routines are computed from a weighted average of available light and leaf area by species. As an example, the stand-level *BGC* input parameter of maximum canopy conductance (g_{max}) is computed by estimating LA for all species on the plot and then calculating a weighted average of g_{max} using the summed LA.

Stand leaf area (LA, m^2) and projected leaf area (PLA, m^2) are summed within and across all vertical canopy layers using the distribution of crown biomass between the height (HT, m) and base of live crown (HBC, m) for each tree on the simulation plot. Canopy layer leaf area is then computed by multiplying the

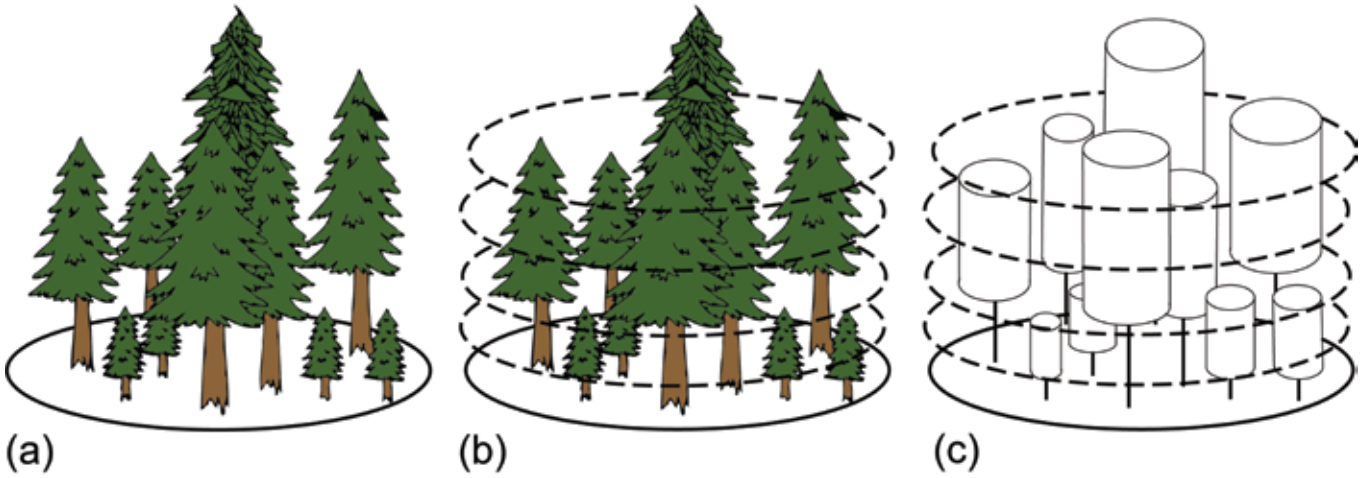

Figure 11. Representation of the forest canopy in FireBGCv2. The model (A) assumes even spatial distribution of trees across the simulation plot, then (B) slices the canopy into vertical layers of a user-specified thickness, and then (C) sums canopy leaf material into the layers using a cylindrical crown calculation.

proportion of the tree crown within a canopy layer (that is, canopy layer width [HSIZE, m] divided by the crown length [CL, m]) by the total leaf area of the tree. This assumes that leaf area is evenly distributed throughout the crown and that each tree crown is cylindrical (Figure 11) (Keane and others 1989, Friend and others 1993). Crown length (CL, m) is obtained by subtracting HBC from the tree height (HT, m). This procedure is repeated for every canopy layer and every tree in the stand. Projected leaf area by canopy layer is computed by dividing leaf area by a weighted PLAI that is calculated by converting from an all-sided to projected leaf area using the factor APPF that is specified in the Species.in file.

The contribution of shrub and herb foliage to canopy layer leaf area is also accounted for in FireBGCv2. The leaf areas of all undergrowth components (ULA, $m^2\ m^{-2}$) are calculated from the following:

$$ULA = (UBIOMASS)(FLBC)(ULF)(USLA) \quad (67)$$

where UBIOMASS is the biomass of the undergrowth component at the height of growing season, FLBC is the fraction of that biomass that is carbon (0.48 in FireBGCv2), ULF is the proportion of that biomass that is leaf material (input parameter specified in the Plant.in file), and USLA is the undergrowth specific leaf area ($m^2\ kgC^{-1}$, also specified in Plant.in and referenced in the Species.in file). Shrub and herb leaf area distribution by canopy layer is computed by multiplying the proportion of the shrub or herb height (UHT, m) in a canopy layer (HSIZE / UHT) by the respective leaf areas. If the canopy layer width (HSIZE) is greater than an undergrowth compartment height (UHT), then all leaf area is allocated to the bottom canopy layer. Shrub and herb crown shape is again assumed to be cylindrical, and it is also assumed that the crown encompasses the entire height of the undergrowth compartment (Keane and others 1989). The vertical distribution of projected leaf area (UPLA) is also computed by multiplying the ULA by the APPF for that undergrowth reference species, as specified in the Plant.in file and taken from the Species.in file. The projected leaf area for trees and undergrowth are summed and this final leaf area (PLA) is stored for reference during the simulation year.

Canopy available light is calculated by first computing the cumulative projected leaf area (CPLA, m^2) for each canopy layer summing from the highest layer to the bottom (ground) layer. The proportion of available light in each layer is then estimated from this cumulative leaf area profile using the Beers-Lambert equation:

$$AL = e^{[-\alpha \frac{CPLA}{PAREA}]} \quad (68)$$

where AL is the proportion of available light in a canopy layer, CPLA is the cumulative projected leaf area (m^2) for a canopy layer, PAREA (m^2) is the area of the simulation plot, and α is the extinction coefficient of the canopy, which is computed as a leaf area weighted average for all species' extinction coefficients (specified in the Species.in file) for the canopy. Values of α in the FireBGCv2 model assume an average over all solar zenith angles and vegetation foliar tilt angles. The AL fractions for each canopy layer are stored for later reference.

Several other canopy-related values are also computed at the beginning of the simulation year. The canopy cover (CC, m^2) is computed by estimating the crown width of each tree using the empirical equations in Moeur (1981), then calculating a projected canopy cover by using the crown width as the radius of a circle. The total area of all tree crown circles are summed to approximate CC. This is divided by the simulation plot area (PAREA) and multiplied by 100 to get percent canopy cover (PCC, percent). This is estimated at the plot and species level. Canopy closure is approximated when PCC is greater than 100.

The canopy layer attributes of CPLA and AL are used throughout the model to simulate a variety of ecosystem processes. The relative amount of available light (AL) is used in the species regeneration, tree growth, and tree carbon allocation. Canopy closure is used as an independent variable in many of the empirical equations that approximate tree attributes, such as crown weight and tree height.

Wildland Fire

Fire behavior is computed at the stand level using a wide variety of methods. The fuelbed simulated at the stand level must be summarized from the stand ground and undergrowth components and then passed to the fire behavior model(s). Fire behavior is then estimated at the stand level. The direct effects of wildfire on ecosystem components and processes are computed in FireBGCv2 as a general cycling of carbon to and from dead and live carbon pools. Carbon and nitrogen losses are computed from the amount of forest floor biomass oxidized by the fire (fuel consumption). Most fuels are not completely consumed by a fire, and the level of consumption is simulated using the *FOFEM* model (Reinhardt and others 1997). Forest floor carbon that is consumed by a fire from any fuel compartment is assumed to be lost to the simulation plot. Tree mortality from fire is computed from the amount of crown scorched and size of the tree. Dead tree carbon and nitrogen not consumed by the fire are added to the forest floor compartments.

Fuel Summary

Prior to the calculation of fire behavior, the stand ground and undergrowth components must be summarized into fuel components for input into the fire behavior models. Live and dead shrub and herb component loadings are summed from the simulation plot's guilds (see "Undergrowth Dynamics" in the "Stand Processes" section) using the following relationships:

$$SHRUB_{dead} = \frac{(\Sigma UBIOMASS_s FDEAD_s)}{PAREA} \quad (69)$$

$$HERB_{dead} = \frac{(\Sigma UBIOMASS_h FDEAD_h)}{PAREA} \quad (70)$$

where $SHRUB_{dead}$ and $HERB_{dead}$ (kgB m^{-2}) are the dead shrub and herb fuel component loadings; UBIOMASS is a summed biomass of all undergrowth components that are shrubs (*s*) or herbs (*h*) as specified by the lifeform for that species in the Plant.in file; PAREA (m^2) is the area of the simulation plot; and FDEAD is the fraction of the appropriate shrub or herb compartment that is dead at the time

of the fire, as specified in the Plant.in file. Values of FDEAD were taken from Brown and Bevins (1986). The remaining shrub and herb biomasses are considered live (fraction not dead, or 1 - FDEAD) and are assigned to the live shrub and herb fuel components.

The stand ground components are already stratified by the fuel components used in the fire behavior models, except for LitterC and LeaffallC, which are added to the 1 hr woody fuel loadings. All loadings are converted to biomass by dividing by the fraction of biomass that is carbon for wood (FRAC_STEM_C_BIOMASS = 0.48). All other fuel characteristics, besides loading, are taken from the fuel model for that stand and site, as specified in the Fuel.in file.

Fire Behavior

In *FIRE-BGC*, wildland fire was dynamically modeled on the simulation landscape using the *FARSITE* spatial fire model (Finney 1996). This model predicts the fire intensity and rate of spread of a fire as it moves across a landscape using the Rothermel (1972) spread model implemented into a spatial domain using Huygen's principles. The spatial data layers of topography, vegetation, weather, and fuels are used to predict fire behavior, and this behavior is fed back to the vegetation to compute consumption, mortality, and smoke. However, the highly complex *FARSITE* model was too computationally intensive for most computers, so Keane and others (1996b) executed it outside of the *FIRE-BGC* program under the *Loki* platform. This proved problematic for the FireBGCv2 revision for two reasons: (1) the simulation of fire using *FARSITE* required extensive computer resources for a 1000-year simulation (there might have been 20,000 to 50,000 fires simulated during this time period), and (2) there were no *FARSITE* libraries to include in FireBGCv2. A new version of *FARSITE* with a simplified computation of fire spread is being developed and it will soon be included in the FireBGCv2 program. Until that time, FireBGCv2 allows fire behavior to be computed at the stand level from either the Rothermel (1972) spread model as implemented in the FireLib library (Bevins 1996) or the Albini (1976) *FIREMOD* model.

The Rothermel (1972) model requires that the surface fuels information be keyed to a surface fire behavior fuel model to compute a realistic fire behavior. To do this, we used the key in the *FVS-FFE* model to key the fire behavior fuel model from the loadings of the stand ground components (Beukema and others 1997). This represents a significant loss in resolution of fuel loadings across stands, and, therefore, tends to homogenize fire behavior predictions across the simulated landscape, especially in long fire return interval ecosystems. We found that more realistic fire behaviors were simulated when the simulated fuel loadings were input to the Albini (1976) model, especially when differences between fuelbeds were small. We simulated running crown fire using the Rothermel (1991) algorithms, but we also simulated passive crown fire if the flame length (see below) was greater than height to the bottom of the live crown for a tree (HBC, m).

Fuel loading is summarized for the stand using the procedures in the "Fuel Summary" section. Fuel moistures are taken from the dynamic fuel moisture simulations described in the "Fuel Moisture" section. These data are then fed to the selected fire behavior model. The model (either Rothermel's or Albini's) then computes several fire behavior characteristics that are saved and used to compute fire effects:

- Flame length (FL, m).
- Spread rate (SR, m sec^{-1}).
- Fireline intensity (FLI, kW m^{-1} fireline).
- Scorch height (SH, m).
- Crown fire index (CFI).

There are a number of caveats that are associated with this method of fire behavior prediction. First, only headfires are simulated; there is no simulation of

backing or flanking fires. Second, both fire models tend to perform inconsistently when actual (simulated) fuel loadings are used. Next, fuel moisture estimates are somewhat coarse because of the resolution of the NFDRS algorithms. Future modifications will include the addition of new fuel moisture models if optimized for a simulation platform.

Fuel Consumption

The reduction of the forest floor compartments by fire is simulated by the process of consumption (Figure 12), which can be computed using one of two methods. The first method uses static consumption estimates by fuel component, as specified in the Fuel.in for the fuel model assigned to that site as follows:

$$ConsumeC_i = CF_i(GC_i) \quad (71)$$

where ConsumeC is the amount of carbon consumed for stand ground component *i*, CF is the consumption fraction of ground component *i*, and GC is the amount of carbon in ground component *i* (ground components are DuffC, LitterC, W1C, and so on). Under model assumptions, no soil carbon (SoilC, kg C) is consumed. It is important to note that while this method is quick, it is not integrated with climate, vegetation, and fire behavior.

The second and preferred method of computing fuel consumption is with the embedded *FOFEM* model (Reinhardt and others 1997). The *FOFEM* consumption routines were integrated into the FireBGCv2 code using dynamic link libraries, and the state variables in FireBGCv2 were linked to the input fields in *FOFEM* to simulate fuel consumption using the *BURNUP* model that is integrated in the *FOFEM* code (Albini and others 1995, Albini and Reinhardt 1995). Consumption of all FireBGCv2 litter and woody fuel components is computed using *BURNUP* algorithms, while duff consumption is computed with the *FOFEM* equations.

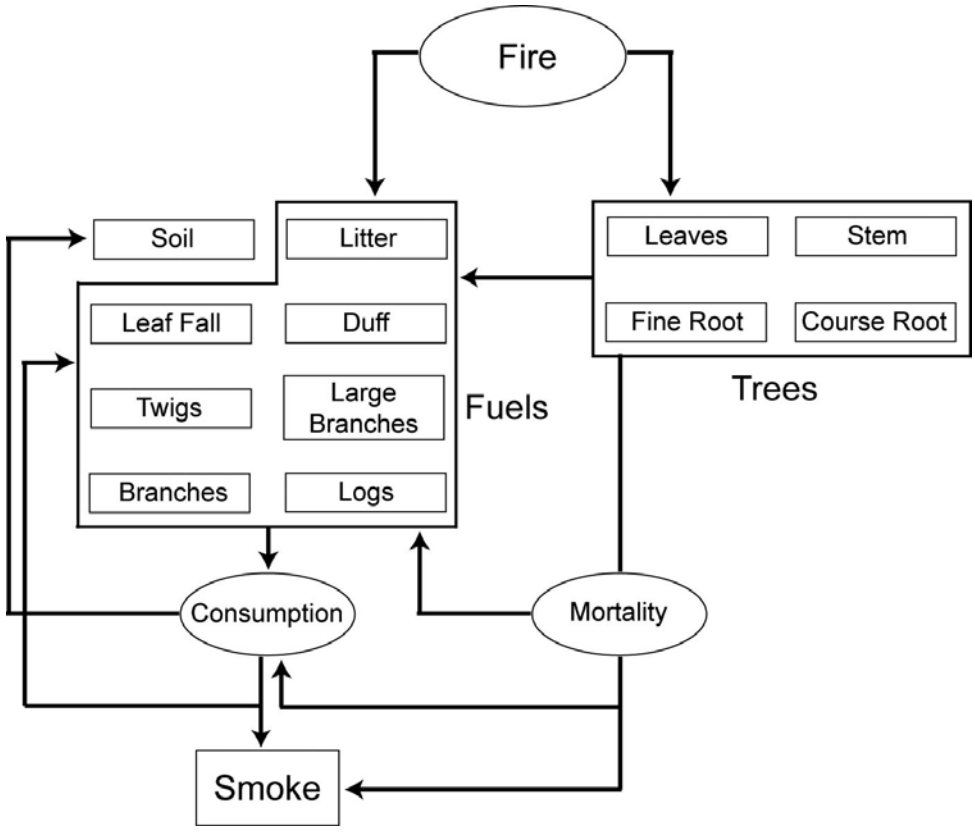

Figure 12. Simplified diagram that shows fire effects of fuel consumption on stand forest floor components.

Carbon and Nitrogen Cycling

All consumed fuel is removed from the ground components to update the stand-level carbon pools (Figure 12). The cycling of nitrogen after fire is simulated in the same manner as carbon cycling, except that some nitrogen from the consumed nitrogen pools goes to the available nitrogen pool (Grier 1975, Pehl and others 1986, Schoch and Binkley 1986). First, the amount of nitrogen in each ground component is calculated from the carbon:nitrogen ratios entered in the Species.in file and summarized for the canopy (see the "Canopy Dynamics" section). Fuel consumption fractions computed from *FOFEM* or input as CF in the Fuel.in file are multiplied by the computed nitrogen amounts for each ground component to obtain the amount of nitrogen lost from those compartments. These estimates are then multiplied by a volatilization fraction (kgN kgN^{-1}) to obtain the actual loss of nitrogen from the site. Nitrogen not volatilized becomes available for plant growth and is added to the available nitrogen pool ($AVAIL_n$, kgN). The volatilization fraction is specified per site in the Site.in file and its values can be taken from Klemmedson and others (1962), Covington and Sackett (1984), Ryan and Covington (1986), Little and Ohmann (1988), Kutiel and Shaviv (1992), and Groeschl and others (1993). Nitrogen losses and contributions to the available nitrogen pool from the undergrowth biomass pools are also computed using the same method.

Smoke

Smoke is simulated in FireBGCv2 by multiplying the consumption of the fuels by specific emission factors (Figure 12). Unlike the previous version (*FIREBGC*), which had smoke emission factors as parameters in the fuel models (Fuel.in input file), FireBGCv2 emission factors are hardwired in the code. The equation for predicting smoke is:

$$SMOKE_i = (CONSUME_l EF_{li}) + (CONSUME_d EF_{di}) \quad (72)$$

where SMOKE is the amount of smoke emissions for *i* element (kg), $CONSUME_l$ and $CONSUME_d$ are live and dead fuel consumption estimates (kg), and EF represents the live (l) and dead (d) emission factors for *i* element (kg consumed kg $element^{-1}$) (Table 4). This smoke is multiplied by the stand area to get a total amount of smoke for the stand. There are five smoke elements in FireBGCv2: PM2.5 (particular matter below 2.5 microns), PM10 (PM below 10 microns), methane, carbon monoxide, and carbon dioxide (Table 4). The program stores and sums all smoke emissions and it outputs results in kg for the entire landscape.

Table 4. Emission factors for the five smoke elements. PM2.5 is all particulate matter less than 2.5 microns in diameter, PM10 is all particulate matter less than 10 microns in diameter, CH4 is methane, CO is carbon monoxide, and CO2 is carbon dioxide.

	Emission factors (kg smoke kg^{-1} consumed)	
Smoke elements	**Dead fuel**	**Live fuel**
PM2.5	22.64	22.64
PM10	26.71	26.71
CH4	13.76	13.76
CO	301.72	301.72
CO2	1228.1	1228.1

Management Actions

As mentioned in the "Landscape Processes" section, three management actions are implemented in FireBGCv2–clearcutting, partial cutting (thinning, selection, and seed tree, for example), and prescribed burning. Both the clearcut and partial-cut actions allow prescribed burning as another post-cutting treatment. The details of the management actions are specified in the Manage.in file. The landscape-level information is used to determine whether a treatment should be implemented for a stand, while the stand-level information is used to decide how to treat the stands that are selected, using a set of treatment parameters (PARM1, PARM2, PARM3, and PARM4). The following paragraphs describe treatment implementation at the stand level and the parameters needed to perform this implementation in the model.

A clearcut is implemented in FireBGCv2 by killing and removing all of the trees in a stand (represented by a simulation plot) that are above a minimum DBH (PARM2) and removing trees that are above a minimum residual DBH (PARM1). All material from trees above the residual DBH is taken offsite, leaving only slash material that is a fraction of the total crown weight as specified by PARM3 (fraction of crown biomass left on the stand). This material is added to the appropriate ground biomass compartments. If a prescribed burn is implemented after the clearcut the target intensity of that burn (kW m^{-1} fireline) is specified in PARM4, and the program simulates tree mortality, fuel consumption, and soil heating using that input intensity. Treatment can be prioritized by tree species in the last line of each treatment defined in the Manage.in file, where 0 means the species is cut and 1 signifies that this species is retained.

A partial cut is implemented in the model by killing and removing all trees in the stand that are between a minimum (PARM1) and maximum (PARM2) DBH, where PARM3 is the fraction of the tree's crown biomass that is added to the ground biomass components. A prescribed burn can be specified by entering a number greater than zero in PARM4–this represents the fireline intensity of the desired prescribed burn. Treatment prioritization by tree species occurs as described above.

Prescribed burning without cutting is the third treatment type defined in the model. The minimum (PARM1) and maximum (PARM2) fireline intensity is specified in the Manage.in file, and the program randomly selects a fireline intensity between these two parameters for each stand eligible for treatment. Fire effects, such as fuel consumption and tree mortality, are computed from this simulated intensity and the fuel moistures entered for the fuel model.

FireBGCv2 computes a number of treatment statistics as output, including total area treated by each treatment type and the cost of implementing each treatment for each simulation year.

Wildlife

Wildlife dynamics are simulated in FireBGCv2 using a habitat suitability approach in which all combinations of stand-level cover type and structural stage define a matrix of suitability values for specified wildlife species. Cover type is determined from the plurality of basal area for each tree species on the simulation plot and structural stage is determined by the distribution of DBH of the trees on the simulation plot. The habitat suitability indices can be of any scale, such as 0 to 3, or 1 to 10, or 0 to 100, depending on the objective of the wildlife analysis. Lower values indicate low suitability and higher values represent areas of high suitability for a particular wildlife species. Any number of wildlife species can be included in the simulation and specified in the Wildlife.in file, along with associated index values for cover type and structural stage. The FireBGCv2 program then computes a suitability value for each stand based on its cover type and structural stage, stores this value for every stand on the simulation landscape, and

outputs map and tabular data summaries at user-defined intervals. These output data can be summarized or displayed across the entire simulation landscape (see the "Demonstration" section).

Wildlife suitability can also be computed at the tree scale by summarizing suitability values for each tree and undergrowth component on the simulation plot by species and structural stage categories. An average suitability index across all trees and undergrowth guilds is then computed and stored for the stand. For example, for a Douglas-fir tree of 15 cm DBH, the model keys to a Douglas-fir cover type and a pole structural stage, and the suitability index for this combination is stored and averaged across all trees and undergrowth components. All undergrowth components are treated as seedlings. Users can specify stand- or tree-level wildlife habitat suitability calculations in the Sim.in file.

Species Processes

Regeneration

Establishment of new trees on the simulation plot is partially accomplished at the species level. Climate and stand conditions are evaluated each year at both landscape and stand levels to determine establishment success of a tree species. Species regeneration is governed by many processes, including seed availability, serotiny, sprouting ability, seedbed condition, antecedent weather, and cone crop abundance. All of these factors are simulated as reduction factors that reduce a maximum regeneration potential (SAP_{max}, saplings m^{-2}) by species. In FireBGCv2, there are three types of regeneration mechanisms for tree species: (1) wind dispersed seed, (2) serotinous seed, and (3) sprouts. Species can have multiple regeneration mechanisms in the model.

Sprouting Species

All species are assigned a sprouting ability in the Species.in file using an ordinal index that ranges from zero (no sprouting) to three (prolific sprouter). In FireBGCv2, sprouting can only occur if a tree dies; there is no spontaneous sprouting from live trees. Trees can die from being harvested (if management activities are specified by user), from being burned (in a management activity or wildfire), or from natural causes (as described in the "Mortality" section in "Tree Processes"). FireBGCv2 simulates a maximum of one sprout from a dead tree (Prentice and Leemans 1990), but there are modifications to the model to increase that number, pending the availability of the new research. One sprout per tree is a good assumption for many Rocky Mountain tree species, with the exception of aspen, because many sprouts never make it to 1.37 m tall (upper height threshold for seedlings). In addition, there are a few existing sprouting studies for western U.S. ecosystems that will provide for more robust parameterization, and model efficiency is increased by reducing the number of new saplings (Pennanen and Kuuluvainen 2002).

The success of a sprout is governed by two factors—shading and stand density—that are simulated as regeneration reduction factors (Kercher and Axelrod 1984). The shading reduction factor (rSHADE) is computed from the stand projected leaf area index (PLAI) using the following set of equations:

$$rSHADE = e^{-0.8PLAI} \text{ for shade intolerant species} \quad (73)$$

$$rSHADE = e^{-0.25(PLAI+1)} \text{ for moderately shade intolerant species} \quad (74)$$

$$rSHADE = e^{-0.25(PLAI-0.2)} \text{ for shade tolerant species} \quad (75)$$

where shade intolerant species have shade tolerance indices of 1 or 2 as specified in the Species.in file, moderately shade tolerant trees have an index value of 3, and shade tolerant species have index values of 4 or 5. The stand density reduction factor (rDENS) uses both a leaf area and a basal area scale to determine sprouting success. The current stand's PLAI is scaled to the maximum LAI that is entered in the Site.in file and this fraction is subtracted from 1.0. The stand's current basal area is also divided by the maximum basal area (specified in the Site.in file), and this fraction is subtracted from one. The factor rDENS is computed as the minimum between these two scalars.

A probability of sprouting (P_{sprout}) is calculated by multiplying a maximum sprouting potential ($SPROUT_{max}$) by the two regeneration reduction factors (Liu and Ashton 1995). The $SPROUT_{max}$ is computed by scaling the ordinal sprouting index to the following values: 0.0, 0.5, 0.7, and 1.0. For example, if the sprouting index is assigned a value of 2.0 for a species in the Species.in file, $SPROUT_{max}$ is equal to 0.7, and if the sprouting index is 0.0, $SPROUT_{max}$ is equal to 0.0. The final calculation of P_{sprout} is the product of $SPROUT_{max}$, rDENS, and rSHADE. This probability is compared to a random number, and if the random number is less than P_{sprout}, a sprout is simulated at that dead tree.

Serotinous Species

Serotiny is simulated in FireBGCv2 using an input parameter called pSEROT that is specified in the Species.in file. The variable pSEROT describes the proportion of cones on a tree that are serotinous (cones that only open after a fire). A reduction factor (rSEROT) is calculated from the pSEROT input value by subtracting pSEROT from one. In the tree regeneration routine, the effect of cone serotiny depends on whether the current simulation year is a fire year or non-fire year. A fire year is when the number of years since last fire (YSF, year) for a stand is greater than the input lag year (LAG, year), as specified in the Site.in file. If the year is a non-fire year, rSEROT is used as a reduction factor (1 - pSEROT) to reduce a maximum number of saplings for a species (see the next section), and the reduction factor rDSUR (duff survival reduction factor) is set at 0.01 to reflect the marginal survival of serotinous species in duff. During fire years, rSEROT is set at 1 - pSEROT and then multiplied by 10.0 to reflect the great amount of seed that is contained in the canopy.

Species Regeneration Processes

New trees of any species can only be established on the simulation plot if several environmental criteria are met. First, the species must be experiencing an abundant cone crop, as simulated at the landscape level and described in the "Landscape Processes" section. Next, the last acceptable spring frost date for the species ($FROST_{spring}$, Julian date) is compared with the latest frost that occurred during a simulation year (Hanninen 1995). The earliest acceptable fall frost for the species ($FROST_{fall}$) is also compared with the earliest autumnal frost for that simulation year. If there is a late spring frost or an early fall frost, then no tree regeneration is simulated that year for that species. The latest and earliest frost is evaluated relative to the midpoint of the species' growing season (GS_{mid}, year-day), as computed from the average of the *leaf out* and *leaf fall* Julian dates. These input values are specified in the Species.in file if the user wishes to not use the dynamic phenology routines of White and others (1997). The latest spring frost is the last frost that occurs before GS_{mid}, and the earliest autumnal frost is the first to occur after GS_{mid}.

Because stand-replacement fires often render a site inhospitable for sapling establishment (Agee and Smith 1984, Arno and others 1985), tree saplings can't become established until an adequate time has elapsed since a major disturbance. The subsequent mitigation of site conditions for tree ecesis is a complex process and difficult to model. This process is indirectly modeled in FireBGCv2 through the use of a waiting period, called the regeneration lag time (LAG, years), that is

input to FireBGCv2 from the Site.in file. Trees will not be established in the simulation plot until LAG number of years have elapsed after a stand-replacement fire (defined as fires causing 98 percent fire-caused tree mortality) (Agee and Smith 1984). Regeneration lag times often exceed 30 years in some upper subalpine ecosystems (Little and others 1994).

As mentioned, the actual number of trees established on the simulation plot for any species is calculated as a reduction of maximum sapling establishment using scalars that indirectly represent environmental effects on tree species ecesis (Keane and others 1989, Urban 1990). The annual maximum sapling density (SAP_{max}, saplings m^{-2}) is specified according to site in the Site.in file and describes new trees across all species. Values for this parameter can be taken from regeneration studies; the values used in *FIRE-BGC* simulations were taken from Alexander (1985), Arno and others (1985), Knapp and Smith (1981), Pfister and Shearer (1978), and Shearer (1975, 1985).

The SAP_{max} parameter is often tuned to improve model efficiency. It is common for many saplings to be established on the plot during a FireBGCv2 simulation and this requires a great deal of memory and simulation time. However, in the model as in real life, most of these saplings will eventually die due to unfavorable environments. The SAP_{max} parameter can, therefore, be altered or reduced to ensure that a realistic number of saplings become trees while also reducing simulation time and memory use. The FireBGCv2 model uses several scalars to reduce the input SAP_{max} parameter value.

The first regeneration scalar evaluates the effect of duff and litter depth on sapling survival for a species. This scalar (rDSUR) is calculated from a modification of Boyce (1985) empirical sapling survival equations of the form:

$$rDSUR = \frac{\alpha - (\beta DEPTH)}{\alpha} \tag{76}$$

where α and ß are regression coefficients stratified by species and taken from Boyce (1985). These coefficients are specified in the Species.in file. DEPTH is the depth of the duff and litter layer (cm) and is computed from the following formula:

$$DEPTH = \frac{1}{100(PAREA)(FDC)}\left[\frac{LitterC}{BULK_l} + \frac{DuffC}{BULK_d}\right. \tag{77}$$

where PAREA is the area of simulation plot (m^2), FDC is the fraction of the duff and litter biomass that is carbon (held constant in FireBGCv2 as 0.48), LitterC and DuffC are the amounts of carbon in the litter and duff forest floor compartments (kgC), and $BULK_l$ and $BULK_d$ are the bulk density (kgB m^{-3}) of the litter and duff forest floor layers, respectively, as specified in the Fuel.in file for each fuel model assigned at the site level. Bulk densities are taken from Brown (1981).

The effect of shade on species establishment is represented in the second regeneration scalar (rSHADE) taken from *FIRESUM*. This scalar uses the shade tolerance index of a species to key to one of these equations:

$$rSHADE = e^{-1.2PLAI} \text{ for very shade intolerant species } (index = 1) \tag{78}$$

$$rSHADE = e^{-0.4PLAI} \text{ for shade intolerant species } (index = 2) \tag{79}$$

$$rSHADE = e^{-0.25PLAI} \text{ for moderately shade tolerant species } (index = 3) \tag{80}$$

$$rSHADE = e^{-0.15PLAI} \text{ for shade tolerant species } (index = 4) \tag{81}$$

$$rSHADE = e^{-0.05PLAI} \text{ for very shade tolerant species } (index = 5) \tag{82}$$

where PLAI is stand projected leaf area index (m^2 m^{-2}) for all trees and undergrowth. Graphical representations of these equations show that shade tolerant species have the best chance of establishing under a dense canopy (Bossel and others 1991, Bossel 1994).

The third scalar (rDENS) adjusts sapling establishment based on an index of crowding in the stand. The scalar is computed from the minimum of two indices that indirectly assesses crowding using leaf area and stand density. The algorithm is as follows:

$$rDENS = MIN\left[\left\langle \frac{PLAI}{LAI_{max}} \right\rangle, \left\langle \frac{BA}{BA_{max}} \right\rangle\right] \quad (83)$$

where PLAI is the stand's projected leaf area index (m^2 m^{-2}), LAI_{max} is the maximum leaf area index for the site (m^2 m^{-2}), BA is the instantaneous stand basal area (m^2 ha^{-1}), and BA_{max} is the maximum stand basal area (m^2 ha^{-1}). Values for BA_{max} and LAI_{max} are specified in the Site.in file.

The next scalars are computed at other scales in the model. The seed dispersal scalar (rDIST) represents the chance of tree species' seed falling within the stand (P_d). This parameter is detailed in the "Seed Dispersal" section within "Landscape Processes." In short, rDIST is set to the minimum of 1.0 or P_{dist}. The influence of serotiny on seed dispersal and availability is simulated using the scalar rSEROT, which is approximately the level of serotiny on the landscape for that species during non-fire years; and during fire years, this value is set to 10.0 (see the "Serotinous Species" section).

The final estimate of saplings established in the simulation plot is the product of all regeneration scalars and maximum sapling density:

$$SAP = (SAP_{max})(rDSUR)(rSHADE)(rDENS)(rDIST)(rSEROT) \quad (84)$$

where SAP is the number of saplings established on the simulation plot for that tree species (saplings $PAREA^{-1}$). The model ensures that the number of trees established across all species does not exceed SAP_{max} by keeping a running sum of the number of trees established across all species and then scaling the number of saplings for regeneration across all species to SAP_{max}. The number of new saplings to add to the simulation plot are stored in an array and passed to the tree regeneration routine for establishment (see the "Regeneration" section in "Tree Processes").

Whitebark pine regeneration is computed differently from other tree species because the seeds of this pine are disseminated by the Clark's nutcracker rather than being dispersed by the wind like all other species. The whitebark pine regeneration module in FireBGCv2 simulates the effects of seed crop, nutcrackers, and light on whitebark tree sapling establishment. A complete discussion of the whitebark pine regeneration algorithm is presented in Keane and others (1990a, 1990b). Parameters that quantify these algorithms are contained in the Pial.in file.

Tree Processes

Regeneration

The FireBGCv2 tree regeneration routine uses simulated results from many scales to predict the number of new trees to add to the simulation plot. Cone crop occurrence and seed dispersal probabilities are estimated across the landscape from data summarized at the stand level. Sapling establishment and survival are evaluated at the species level (see the "Regeneration" section in "Species Processes"), and the number of new trees to add to the simulation plot by species is estimated at the tree level. The number of saplings that are established on a simulation plot is SAP, as detailed in the "Species Processes" section.

Each new tree established on the simulation plot, whether it originated from a seed or sprout, is randomly assigned a diameter (DBH, cm) between 1 and 2 cm using a uniform probability distribution. The initial tree age (years), height (m), and height to bottom of live crown (m) are taken from parameters specified in the Species.in file. The initial ecophysiological characteristics (XT) of established saplings are then calculated from structural characteristics using empirical equations as detailed in the "Program Implementation" section.

Growth

Tree growth in both diameter and height is simulated differently for each of the three succession model drivers. The simple gap model simulates growth using growth reduction factors or scalars. The mechanistic gap model uses estimates of carbon growth based on estimates of photosynthesis computed at a daily time step. The *BGC* model proportions carbon to trees then stems to compute growth in diameter and height.

Simple and Mechanistic Gap Models

Tree growth in the simple and mechanistic gap model was taken directly from the *FIRESUM* model (Keane and others 1989). In that model, diameter and height growth are simulated as a reduction from a maxima that is taken from the literature. In this routine, there are four reduction factors to account for available water, light, crowding, and temperature.

The light reduction factor (rSHADE) is calculated from a light response function that is keyed from the shade tolerance index specified for each species in the Species.in file:

$$rSHADE = a(b - e^{-cAL})(AL - d) \tag{85}$$

where AL is the light scaled from 0.0 (no light) to 1.0 (full sunlight) that is available the top of the crown of a tree; and a, b, c, and d are coefficients fitted to a growth reduction equation from previous gap modeling studies. AL is computed for vertical slices of the canopy each year of the simulation at the stand level (see the "Canopy Dynamics" section in "Stand Processes"). Hardwired values in FireBGCv2 for the a, b, c, and d coefficients are listed in Table 5.

The rWATER reduction factor to account for the availability of water is simulated from the actual and potential evapotranspiration (AET and PET, kgW m^{-2}). The function uses the ratio of AET and PET to compute rWATER:

$$rWATER = 1 - \left[\frac{(1 - WRS)}{(1 - WSO)}\right]^{v} \tag{86}$$

where WRS is the ratio between AET and PET (AET/PET) bounded between 0.0 and 1.0, WSO is the minimum ratio for that tree species as input in the Species.in file, and v is the exponent set at 2.0 for current modeling efforts. AET is not simulated in

Table 5. Coefficients for the available light reduction function used to compute diameter and height growth.

	Regression coefficients			
Shade tolerance class	***a***	***b***	***c***	***d***
1	1.60	1.10	1.20	0.25
2	1.22	1.00	2.00	0.13
3	1.11	0.90	3.00	0.07
4	1.04	0.80	6.00	0.04
5	1.01	0.75	10.00	0.01

the simple gap model so total annual precipitation is used instead of AET and PET is calculated from annual average temperatures (Keane and others 1989).

Temperature effects are simulated using the reduction factor rTEMP that is calculated from degree-days (DD) using the following formula:

$$rTEMP = \left[\frac{(DD - DD_{min})(DD_{max} - DD)^{\upsilon}}{(DD_{opt} - DD_{min})(DD_{max} - DD_{opt})^{\upsilon}} \right] \quad (87)$$

and

$$\upsilon = \frac{(DD_{max} - DD_{opt})}{(DD_{opt} - DD_{min})} \quad (88)$$

where DD is the current year's degree-days; and DD_{min}, DD_{opt}, and DD_{max} are all input parameters entered in the Species.in file that define the temperature reduction factor curve and that represent the minimum, optimum, and maximum degree-days for that tree species. These parameters are usually estimated from weather stations that are on the edge of the geographic (latitudinal) or elevation range of the species. Degree-days (^{o}C day) is calculated using average daily temperature and a base of 3 ^{o}C ($DD = \sum \min[(T_{ave} - 3), 0.0]$).

The crowding factor (rCROWD) is calculated from the minimum of two indices that indirectly assess the effect of crowding on tree growth using leaf area and stand density (similar to that used for regeneration simulation detailed in the "Species Processes" section). The algorithm is as follows:

$$rCROWD = MIN\left[\left\langle \frac{PLAI}{LAI_{max}} \right\rangle, \left\langle \frac{BA}{BA_{max}} \right\rangle \right] \quad (89)$$

where PLAI is the instantaneous projected leaf area index of the stand (m^2 m^{-2}), LAI_{max} is the maximum leaf area index for the site (m^2 m^{-2}), BA is the instantaneous stand basal area (m^2 ha^{-1}), BA_{max} is the maximum stand basal area (m^2 ha^{-1}), and MIN is a function that picks the minimum value between the two values. Values for BA_{max} and LAI_{max} are specified in the Site.in file.

Tree diameter growth (DINC, cm) is computed as a reduction from a maximum diameter increment ($DINC_{max}$) using the four growth reduction factors, as shown below:

$$DINC = (DINC_{max})(rSHADE)(rWATER)(rTEMP)(rCROWD) \quad (90)$$

where DINC is DBH growth increment (cm). The maximum increment is computed from the maximum and current DBH using the following function:

$$DINC_{max} = \frac{(G)(DBH)[(1 - \frac{(DBH)(HT)}{(DBH_{max}HT_{max}}]}{274 + 3aDBH - 4bDBH^2} \quad (91)$$

where *G* is computed from equation 3 in Botkin and others (1972), and the *a* and *b* coefficients are computed from equation 5 in Botkin and others (1972). Parameters *G*, *a*, and *b* use AGE_{max} for their derivation. The parameters DBH_{max} and HT_{max} are input values entered according to species in the Species.in file. DINC is then compared to a minimum increment $DINC_{min}$ (parameter entered according to species in the Species.in file), and the highest value is used, but if the DINC is less than $DINC_{min}$, the tree stress counter adds one year (in essence, this signals that the tree is under stress).

The increase in height growth is simulated from the Botkin and others (1972) equation:

$$HT = 137 + aDBH - bDBH^2 \quad (92)$$

where *a* and *b* coefficients are computed from equation 5 in Botkin and others (1972). Growth in leaf area and branchwood is calculated from the crown biomass equations (Brown 1978) using the new DBH and HT values. Last, the model increments the tree's age (AGE) by one year.

BGC Model

Tree diameter (DBH, cm) and height (HT, m) growth increments are computed at year's end from the estimates of carbon growth proportioned to the tree stem carbon compartment (StemC, kgC) (Gordon and Larson 1968). First, tree age is incremented by one year. Then, the annual photosynthesis (PSN) and respiration (MR) stored for each tree are used to calculate a net primary productivity for that tree (NPP_t, kgC). This NPP_t is summed across all trees in the stand to calculate "bottom-up" stand-level NPP_s value. Then, the annual *BGC* stand-level estimates of production (NPP_{bgc}) are adjusted for plot area and then allocated to each tree based on the ratio of NPP_t / NPP_s, as in the following equation:

$$NPP_{tBGC} = NPP_{BGC} \frac{NPP_t}{NPP_s} \tag{93}$$

This tree-level carbon (NPP_{tBGC}, kgC) is then allocated to the tree's components (LeafC, FrootC, CrootC, DeadstemC, and LivestemC) using the allocation parameters for that species as specified in the Species.in file and the allocation algorithm from Schwalm and Ek (2004), which allocates carbon based on all-sided leaf area, shade tolerance, and species life form. The understory is also included in this computation of carbon allocation.

Tree growth in diameter and height is then computed from the difference in stem carbon (StemC = LivestemC + DeadstemC) from the previous year to current year. First, a minimum and maximum DBH and HT are computed to bound growth. The minimum diameter (DBH_{min}) is set from the parameter entered according to species in the Species.in file, and the maximum DBH (DBH_{max}) is set at three times the average diameter growth (computed as DBH / AGE). A maximum tree height (HT_{max}) is calculated using equations in Milner (1992) and a scaling routine, which uses the current year's height, tree age, site index (as input to FireBGCv2 in the Site.in file), species site index (as specified in the Species.in file), and shade tolerance to compute a new height. Basically, tree height (HT) is calculated from the Milner (1992) equations using AGE and site index (selected as the minimum between the site and species input values) and then reduced by the shade reduction factor rSHADE, as calculated from the same formulae described in the previous gap model tree growth section, which uses the available light at the top of the crown (AL) and shade tolerance class (specified in Species.in). Two heights are computed: maximum height (HT_{max}) that is calculated by assigning AL = 1.0, and a lower height (HT) that is calculated using the AL for the canopy layer at the tree's top.

Next, the diameter increment (DINC) is calculated from the change in stem carbon (StemC) and the change in tree height from the following:

$$DBH_{new} = \sqrt{\frac{StemC_{new} HT_{old} DBH_{old}^2}{StemC_{old} HT_{new}}} \tag{94}$$

where DBH_{new} is the new diameter (cm), DBH_{old} is the diameter last year (cm), $StemC_{old}$ and $StemC_{new}$ are last and this year's stem carbon, and HT_{new} and HT_{new} are last year's and this year's tree heights (m). This approach assumes a truncated frustum stem geometry and uniform diameter growth over the entire stem. The StemC is calculated from the tree's live and dead stemwood carbon; the previous year's StemC ($StemC_{old}$) is stored in memory.

Next, the minimum possible diameter (DBH_{min}, cm) for this year is compared to the new DBH (DBH_{new}), and if DBH_{new} is less than DBH_{min}, a DBH_{new} is recomputed based on shade tolerance. If shade tolerance class is shade intolerant

(class one or two), DBH_{new} is set to DBH_{min} and HT_{new} is recomputed based on the same proportional relationship shown above. If it is any other shade tolerance class, then HT_{new} is set to HT_{old} + 0.01 m and DBH_{new} is computed using the proportional formula above. In addition, trees with a DBH_{new} that is less than the DBH_{min} are assumed to be experiencing growth-related stress and the stress counter Y_{stress} is incremented.

The last computation in the dimensional growth analysis is the modification of tree crown height (HBC, m). The model calculates the available light conditions (0.0 to 1.0) at the bottom of the canopy from the vertical distribution of available light as detailed in the "Canopy Dynamics" section. If the shade tolerance class of the tree species is intolerant (class one or two) and the available light is less than 0.1, then the HBC is increased by the simulation height increment (HINC) as input by the user in the Sim.in file. For shade tolerant species (class three, four, or five), the available light value has to be less than 0.02 for crown pruning. All crown material is added to the ground carbon layers by crown fuel category.

Mortality

There are four causes of tree mortality that are stochastically simulated in FireBGCv2—random, stress, fire, and pathogens (Keane and others 1989). Random mortality is the chance of death from random events, such as endemic insect attack, windthrow, or other local perturbations that a tree experiences throughout its lifetime (Monserud 1976, Franklin and others 1987, Hamilton 1990). The probability of random mortality (P_{random}) is calculated by the equation:

$$P_{random} = \frac{\varepsilon}{AGE_{max}} \tag{95}$$

where AGE_{max} is the maximum age that can be attained by the tree species and ε is an empirically fitted coefficient (years). This coefficient is estimated based on the assumption that 2.0 percent of the trees (98^{th} percentile) survive to the maximum attainable age for a species. Analysis of stand data from Montana, Idaho, and eastern Oregon suggests that 2.0 percent is reasonable for most western conifers. The value of ε was assumed to be 4.0 for most species to approximate the 2.0 percent estimate. However, stand data collected by Keane and others (1994) found ε closer to a value of 3.0 for whitebark pine.

Stress mortality is tree death resulting from severe stress over long periods. Stress mortality can be caused by water scarcity, insufficient light, or tree crowding (Pedersen 1998). *FIRE-BGC* used the amount of carbon allocated to the stem to evaluate tree stress. In FireBGCv2, a stress counter (Y_{stress}, years) is incremented by one year if the tree cannot grow sufficiently to exceed a minimal diameter growth. For the simple gap model, Y_{stress} is incremented when the current year's DBH increment (DINC) is less than an input minimum ($DINC_{min}$) as specified in the Species.in file. For the mechanistic gap and *BGC* succession models, Y_{stress} is incremented if the NPP for the tree is less than zero. Y_{stress} is then used in the following two-parameter Weibull probability function (Reed and Clark 1979):

$$P_{stress} = a[1 - e^{-bYstress}] \tag{96}$$

where P_{stress} is the probability of mortality resulting from stress, and *a* and *b* are coefficients by shade tolerance class (Table 6). Stressed trees become healthy after experiencing three consecutive years of diameter growth above the minimum allowable growth (DINC>$DINC_{min}$ or NPP>0.0).

The last two causes of mortality—fire and pathogens (only blister rust and mountain pine beetles are currently available in FireBGCv2)—are presented in the following sections. Pathogens include both insects and disease in this modeling effort. The probability of mortality from these factors is represented by P_{fire} for fire-caused mortality, P_{rust} for blister rust, and P_{beetle} for mountain pine beetle-caused mortality.

Table 6. Stress mortality function parameters by shade tolerance classes that are used to calculate tree death from stress-related causes.

	Regression coefficients	
Shade tolerance class	***a***	***b***
1	150.0	2.0
2	180.0	2.0
3	200.0	2.0
4	240.0	2.0
5	280.0	2.0

Tree death is evaluated separately for each mortality agent. First, a random number (RNUM) is compared to P_{random} and, if RNUM is less than P_{random}, the tree dies. If the tree lives, another random number is compared to P_{stress}, and if the random number is less, the tree dies. This is repeated for P_{fire}, P_{beetle}, and P_{path}. The tree must pass all comparisons to continue to live.

After a tree dies, regardless of the cause of mortality, it contributes its carbon to the forest floor compartments. Foliage (LeafC) and branchwood (W1C, W10C, and W100C) carbon, computed from the Brown (1978) empirical equations, is allocated to the LitterC and DuffC forest floor compartments based on the species needle lignin fraction (see the "Decomposition" section in "Stand Processes"). Woody branchwood carbon is added to the W1C, W10C, and W100C forest floor compartments by size class using Brown's (1978) equations. The tree is then considered a snag, and it is assigned a limited number of the structural carbon and dimensional attributes of the tree at the time of death.

Snags

Once a tree dies in FireBGCv2, it becomes a snag. The only characteristics that are simulated for a snag are its species, DBH, HT, AGE, and WoodC (carbon remaining in the stem after all woody twigs and small branchwood are added to the fuel compartments, kgC). The snag receives the same DBH and HT as the mother tree, but its AGE is set at zero, and its WoodC is estimated from the StemC values previously discussed. A snag's AGE is incremented each year, and a probability of snag fall is calculated using the following relationship:

$$P_{fall} = 1 - e^{-[\frac{AGE}{AGEsnag}]^3} \quad (97)$$

where AGE_{snag} is the maximum age of a snag (year), which is input to the program according to species in the Species.in file. Once a snag falls, all of its WoodC gets added to the W1000C ground pool.

A snag can also be input to FireBGCv2 in the Tree.in file by specifying the health rating (RATE) as the number 4. This will tell the program to make this entry a snag. However, if the rust flag in the Sim.in file is negative, all five-needle pine trees that have a health status of 4 will be input to the program as a healthy pine tree to simulate tree and stand structures before rust mortality.

Phenology

All phenological triggers for each tree are simulated at the site level for each species. Two major phenological events—*leaf fall* and *leaf growth*—require triggers. Event triggers for trees and undergrowth components are differentiated by evergreen or deciduous plant types. Evergreen trees and shrubs keep their needles all year long and drop $1/365^{th}$ of their needles each day throughout the year. They gain new foliage only during the *leaf out* phenological stage, and this gain is dependent on the amount of leaf carbon computed for this tree during the previous

year. In short, each year the model computes a tree's leaf carbon (leafC) from allometric equations using DBH and height. This LeafC is then stored as $LeafC_{max}$ for that year's simulation. Foliage is lost from LeafC during the *leaf fall* phenological stage by subtracting a proportion of the LeafC (LeafC / leaf retention time, as specified in the Species.in file) for each day of the *leaf out* period (also specified in the Species.in file). During the *leaf out* stage, the same amount of foliage lost during *leaf fall* is added to LeafC. For deciduous shrubs and trees, all foliage is lost during *leaf fall* and gained during *leaf out* stages. The fine roots for these trees follow the same phenology pattern as the leaves. For the herbaceous undergrowth components all foliage dies during the *leaf fall* period and all foliage grows to its full potential during the *leaf out* period.

Wildland Fire

Tree Mortality

Fire-caused tree mortality is modeled as a function of bark thickness and scorch height, which is dependent on fire intensity and wind (Ryan and others 1987, Ryan and Reinhardt 1988). When a fire spreads through an area, it can kill trees by consuming or scorching foliage and killing stem and root cambium (Peterson 1983). The scorching of crown foliage involves killing the needles from heat exposure without consuming them. Sometimes the fire is so intense that tree crowns are entirely consumed by the fire, resulting in immediate tree death. Live crown consumption by fire is assumed to occur if the fire's flame length (FL) is greater than the height to the bottom of the crown (HBC) (Figure 13). If the flame length is lower than the crown, indirect mortality from crown scorch and cambial kill is evaluated.

The degree of crown scorch and cambial kill depends on fire intensity and duration. Ryan and Reinhardt (1988) developed an empirical mortality equation that

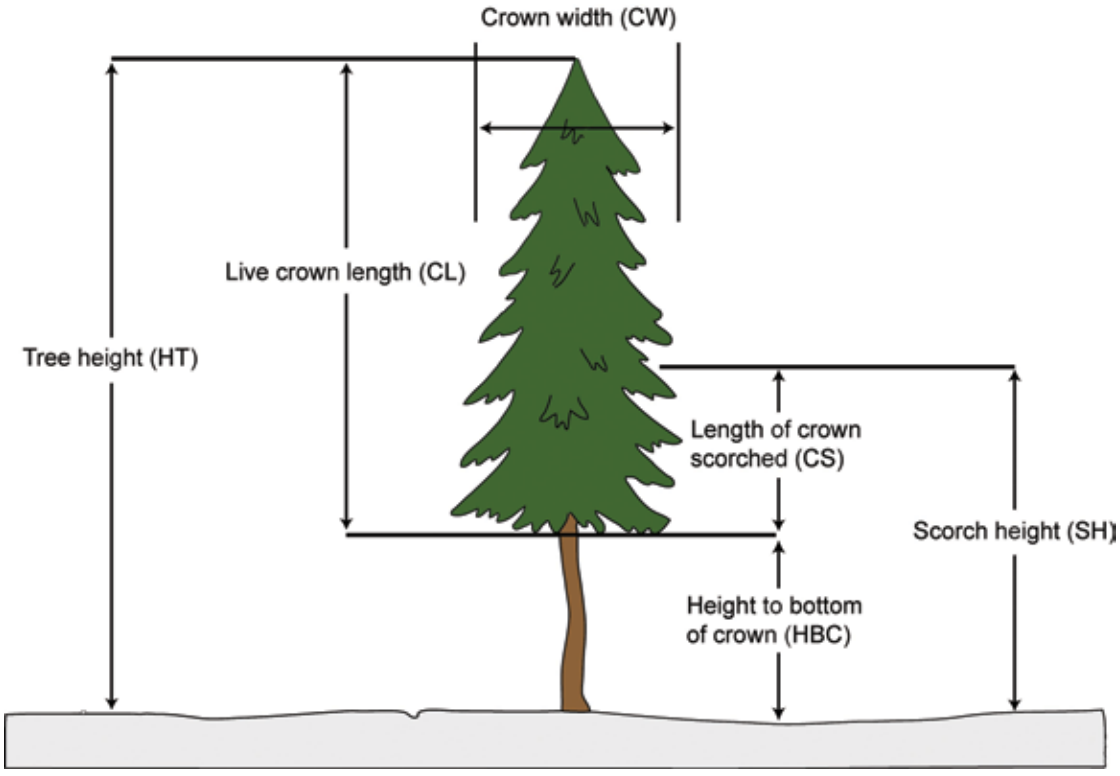

Figure 13. Representation of a tree dimensions in simulating tree mortality in FireBGCv2.

implicitly accounts for both causes of fire death. The equation was implemented in FireBGCv2 as:

$$P_{fire} = \frac{1}{1 + e^{[-1.941 + 6.32(1-e)^{[-BARK_{thick}DBH]} - 0.000535CK^2]}} \quad (98)$$

where P_{fire} is the probability of mortality from fire after one year; $BARK_{thick}$ is the factor that converts DBH to bark thickness (cm bark cm DBH^{-1}), as specified in the Species.in file; DBH is tree diameter (cm); and CK is the percent of scorched or consumed crown volume for the tree (percent). Values for $BARK_{thick}$ can be taken from Lynch (1959), Lange (1971), Myers and Alexander (1972), Faurot (1977), Ryan and Reinhardt (1988), and Reinhardt and Ryan (1989). Tree death is evaluated using a random number approach, as described in previous sections. Scorched crown volume percent (CK, percent) is estimated using the following formula:

$$CK = 100[\frac{CS(2CL - CS)}{CL^2} \quad (99)$$

where CS is the length of crown that is scorched (m) and CL is crown length (m) (Figure 13). This relationship assumes that the crown shape approximates a paraboloid (Peterson 1985). The dimension CS is solved by the equation CS = SH - (HT - CL), where HT is tree height (m), and SH is scorch height (m). Scorch height is calculated from an empirical expression developed by van Wagner (1973):

$$SH = \frac{a(FI)^{1.667}}{(T_{kill} - T_{ave})[b(FI) + c(WIND)^3]^{0.5}} \quad (100)$$

where FI is fire intensity (kW m^{-1}), WIND is wind speed (km hr^{-1}) at mid-flame height, T_{ave} is ambient air temperature (^oC), and T_{kill} is the lethal temperature for tree foliage (assumed as 60 ^oC in FireBGCv2). The constants *a*, *b*, and *c* were derived empirically and are 0.74183 m $^oC^{-1}$, 0.025574 (kW $m^{-1})^{4/3}$, and 0.021433 km^{-1} hr (kW $m^{-1})^{7/9}$, respectively. FI is computed from the Rothermel (1972) spread model, as implemented in the FireLib routines (Bevins 1996) or the Albini (1976) *FIREMOD* routine (see the "Wildland Fire" section in "Stand Processes"). Ambient air temperature for the fire is specified as a constant in the Site.in file. Although the fire mortality equations are robust and allow for a wide range of diameters and species, data for small-diameter (<10 cm) tree mortality are lacking. Since the majority of simulated trees are less than 10 cm DBH, additional refinement of this equation to account for small diameter tree mortality is needed.

A tree's foliage is considered scorched if the flame length (FL) is less than the height to base of live crown (HBC); and conversely, a trees foliage is consumed if FL is greater than HBC (Figure 13). A probability of 0.99 is assigned to P_{fire} if a tree's foliage is consumed. If a tree dies from fire scorching, its foliage and branchwood are added to the appropriate forest floor compartments, and its stemwood becomes a snag. If the crown material is consumed by the fire, a fraction of the crown fuel components gets consumed and the remaining fraction is added to the forest floor. The consumption fractions are specified in the Fuel.in file for live and dead canopy and ground fuels. There is a consumption fraction for the foliage, twigs, branchwood, and large branchwood. The unconsumed portions of the crown compartments are added to the appropriate forest floor carbon and nitrogen compartments. All consumed crown carbon and nitrogen is assumed to be lost from the simulation plot.

Some trees will continue to live even with some crown scorch. In these cases, the scorched foliage is added to the forest floor compartments. The proportion of crown scorched (that is, CK / 100) is multiplied by the tree's leaf carbon (LeafC, kg C) and nitrogen (LeafN, kg N) to obtain the amount of killed foliage to add to the LitterC and DuffC compartments. No branchwood is added to the forest floor. The height to the bottom of crown (HBC) is then adjusted upward proportional to the percent crown kill (CK).

Insects and Diseases

Insect- and disease-caused mortality are the fourth and fifth types of tree mortality simulated in FireBGCv2. FireBGCv2 only simulates tree mortality caused by white pine blister rust (*Cronartium ribicola*) and mountain pine beetle (*Dendroctonus ponderosae*) in high-elevation ecosystems. Details of these mortality algorithms can be found in Keane and others (1989, 1990b). The initial year of blister rust (YRUST) or pine beetle (YBEETLE) epidemic is entered in the Sim.in file. The probability of tree mortality is assessed for each pathogen during the epidemic and tree death is simulated using the methods detailed in the "Mortality" section of "Tree Processes." This submodel of FireBGCv2 was designed so that any new pathogen algorithm can be added with minimal program modification. Most insect and disease mortality algorithms were developed from empirical data using regression analysis. However, future versions of FireBGCv2 will be linked with mechanistic simulation of pathogen dynamics to fully understand the interaction of these disturbance processes on ecosystem function.

White Pine Blister Rust Mortality

The spread of blister rust is modeled at the stand level for each western haplopaxon (five-needle) pine (whitebark pine or western white pine, for example) using a probability of mortality (P_{rust}). Once a rust epidemic has been initiated (see the "Landscape Processes" section), all five-needle pines are evaluated for rust mortality, except those that are rust resistant. The probability of death from blister rust (P_{rust}) is computed from the following equation:

$$P_{rust} = e^{[-0.15DBH]} \quad (101)$$

where DBH is tree diameter (cm). A rust flag for each tree is incremented each year of infection and, if this flag reaches 20 years, the tree is unable to produce a cone crop.

Because blister rust kills only rust susceptible five-needle pines, resistance to the disease is simulated in the model by randomly assigning a portion (set at 1.0 percent in the model) of the five-needle pine trees as rust resistant. There is no cone crop reduction for rust resistant five-needle pines.

Mountain Pine Beetle Mortality

The probability of mortality from mountain pine beetles (P_{beetle}) is calculated each year of a beetle attack using the empirical equations for whitebark pine:

$$P_{beetle} = 0.007664 \text{ (DBH)} - 0.00222 \quad (102)$$

and for lodgepole and ponderosa pine:

$$P_{beetle} = 0.00555(DBH) \quad (103)$$

where DBH is tree diameter (cm). These regression equations were developed from unpublished data provided by the USDA Forest Service, Northern Region, and Gene Amman, Intermountain Research Station. A pine beetle attack ends when the number of surviving pines divided by the number of pines prior to attack is less than a minimum infestation level (5 percent).

Program Implementation

To understand the complexity and detail involved in generating acceptable simulation results from FireBGCv2, it is important to follow the general steps involved for the creation of a simulated dataset (Figure 14):

1. *State your objective*. This is the most important step in the entire process. Succinctly state the objective of your FireBGCv2 simulation to select the most appropriate initial conditions, most accurate parameters, and best response variables to output.
2. *Select response and explanatory variables*. The decision of which variables to include in the output simulation results will make parameterization much easier and more focused. A long list of response and explanatory variables may overwhelm some statistical software packages that are used for results analysis. Response variables are used to answer or complete the simulation objective; they are the variables that best describe differences in between simulation scenarios. Explanatory variables are variables that provide context and explanation on why the response variables differ across scenarios.
3. *Design simulation*. Decide the important simulation specifics such as the landscape extent, pixel size, buffer width, temporal length of the simulation, and output reporting interval. These are decided in the context of the modeling objective, available computing resources, and available modeling expertise. Also, the design of the set of simulation scenarios needed to successfully complete the simulation objective are done at this step.
4. *Gather data*. All models need data for parameterization, initialization, and validation, and it is critical that appropriate and accurate data are available to quantify parameters, compute starting conditions, and test model output for the entire simulation area. If not, a literature search can help quantify those missing parameters or they can be estimated using local experts or statistical modeling.
5. *Parameterize model*. Analyze collected data to quantify parameters for direct input into the model. Be sure to document all sources of information used to quantify each parameter. A scheme will be needed to populate all of the thousands of parameters required by FireBGCv2. For example, Keane and others (1996a) had problems populating species parameters for *FIRE-BGC*, so they used a plant functional types approach where undergrowth and tree species were grouped into plant functional types based on genus, fire adaptations, and morphology. If parameters were unavailable for a species, they used the values for another species in that plant functional type. If those were unavailable, they used a default parameter set.
6. *Initialize model*. Model execution must start from someplace, so many modelers use the current conditions as a starting point for model runs. For example, a vegetation type layer might be overlaid with a potential vegetation map to create the stand map with sites (potential vegetation) that can then be used to initialize a landscape simulation.
7. *Execute model*. Run the model, then run it again, and again. Be sure that all parameters and initial conditions are entered into the model correctly by checking the echo and error files (see the "Model Execution" section). Clean up all error statements and warnings.
8. *Evaluate results*. Always examine model outputs in detail to determine if the model is computing believable and realistic answers. We suggest that a calibration scenario be designed to mimic landscape dynamics over the last 50 years by selecting the weather and landscape initial conditions that best capture this

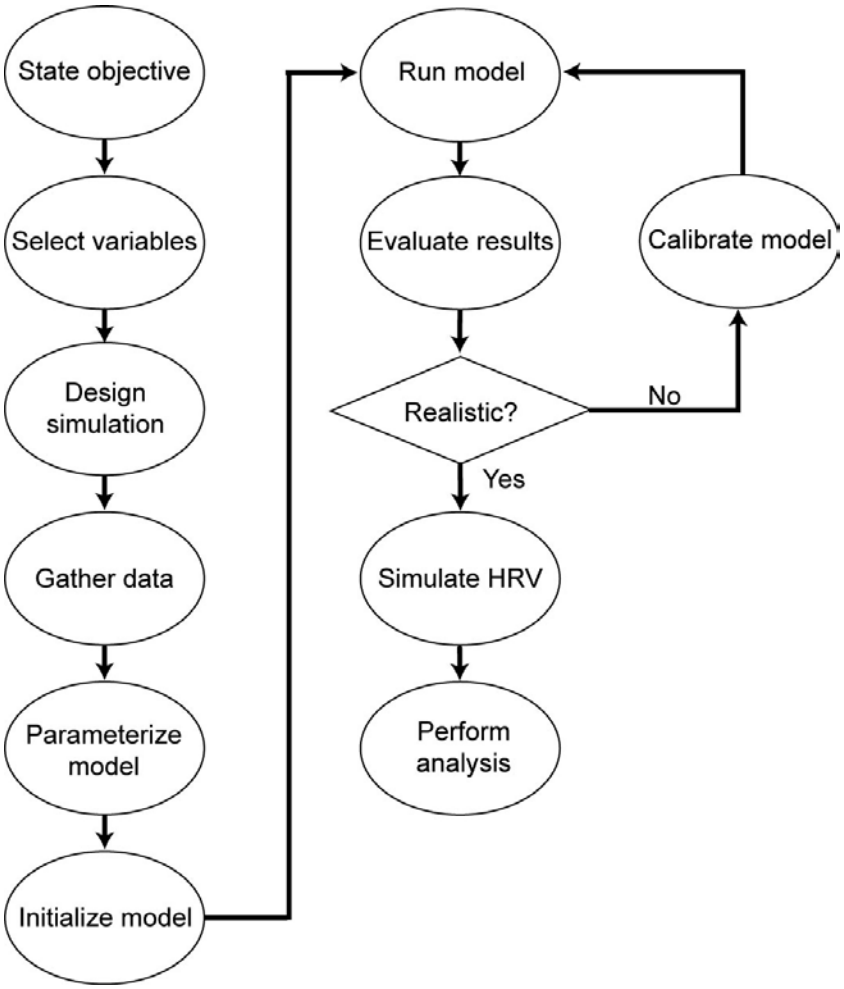

Figure 14. A flow chart to use when calibrating and testing FireBGCv2 output to ensure the most realistic simulations.

recent history. This landscape could be run for 50 years and resultant landscape dynamics can be compared with observed conditions (field data) at the landscape, stand, and tree levels.

9. *Calibrate model*. If unrealistic predictions are generated, then adjust parameters and initial conditions to get more realistic answers. Pay special attention to parameters with high uncertainty, such as those quantified from expert opinion, as they may not be rectified with the entire parameterization. Again, check simulated results against field data to ensure realism. Repeat steps (8) and (9) until satisfied with results.
10. *Simulate results*. The implementation of the entire simulation design should be done using the model. All simulation scenarios should be executed at least five times and results should be averaged to achieve modeling objectives.
11. *Perform analysis*. Use the simulated results in the appropriate analysis to successfully accomplish the simulation objective. For example, the change in response variables between modeling scenarios can be analyzed using analysis of variance techniques.

This entire process could take years for the inexperienced person using complex simulation designs or hours for the experienced modeler using simple, parsimonious scenarios. To simplify the discussion of these steps, we've broken the categories into five major tasks: parameterization, initialization, calibration, simulation, and output analysis.

Parameterization

FireBGCv2 requires the quantification of many algorithm parameters, as is the case with most multi-species mechanistic models (Burk and others 1990, Bossel 1991). However, it is difficult, and sometimes impossible, to gather all of the information needed to parameterize every relationship included in the model. Critical ecophysiological research needed for model parameterization is lacking for most forest species. Therefore, a scheme should be devised to assign parameter values that are taken from well-studied tree species to the less-studied tree species. A suggested scheme involves grouping tree species into similar ecological groups or plant functional types (Diaz and Cabido 1997). Then, if data are not available to quantify a FireBGCv2 species parameter, the parameter for another species in the plant functional type can be used (Kellomäki and Väisänen 1991). Tree species can be grouped according to their role in the successional process using the Minore (1979) classifications. Tree species with similar successional roles seemed to display similar ecological, morphological and physiological qualities (Grime 1966, Drury and Nisbet 1973, Grime 1974, Bazzaz 1979, Grime 1979, Canham and Marks 1985, Wallace 1991). For instance, early seral species tend to have high photosynthetic rates, low tolerance for shade, rapid height and diameter growth, frequent cone crops, long lifespans, and short crown lengths (Grime 1979, Bazzaz 1990). Late seral species appear to show opposite qualities (Finegan 1984, Drake 1991).

We suggest the following scheme for assigning model parameters:

- Perform a literature search on model parameter values and attempt to parameterize as many species as possible. Create a spreadsheet with parameters and reference citations.
- Create a default parameter file for fuels, plants, and, most importantly, species using the results of the literature search and input files from this report.
- Create plant functional types around the modeling objective. If the simulation scenarios emphasize differences in fire dynamics, then the plant functional types should be designed around fire adaptations or survival characteristics.
- Assign parameters from parameterized plants to other un-parameterized species with each plant functional type.
- If no parameters exist for a species or functional type, use the value from the default species parameter list.

Most selected parameters and the initial values discussed next are stored in a suite of ASCII data files that are immediately scanned at the start of simulation for validity and errors. These files are stratified based upon the overall organizational architecture of the model (landscape, site, stand, species, and tree) with examples depicted in the "Input File Structure" section. The names of these input files are specified in the Driver.in file that is specified as an argument in the program execution command line.

Parameterization is the most important task in conducting FireBGCv2 simulations, but there are very few ecosystems, landscapes, and species in the world that have sufficient ecological data across the entire simulation area, and some sort of data synthesis is required to extrapolate existing data across the entire simulation landscape. Comprehensive literature searches and expert consultations are critical in data-poor regions. Model parameters can be approximated from many sources listed here in order of preference:

1. *Measurement*. The actual measurement of a parameter on the landscape that is to be simulated will result in the most credible simulation results.
2. *Literature*. A review of the literature to evaluate the parameter values measured on other landscapes by other studies may provide a suitable alternative, but special attention must be made to ensure that the context of the measurement

best fits the simulation landscape (for example, match vegetation types, topographic settings, and sampling methods). There are also a number of literature syntheses of important model parameters (Hengst and Dawson 1994, Korol 2001, Hessl and others 2004).

3. *Meta-modeling*. Models can be used to estimate parameters for other models. Stage and others (1995), for example, used a growth and yield model (*FVS*) to estimate growth parameters for a gap model.
4. *Iterative modeling*. This is when a parameter is approximated and then input into the model, and the model is run to generate results that are then compared to a reference to determine if the reference agrees with the simulated results. If not, the parameter is incrementally changed until the results match the reference.
5. *Dephi approach*. A parameter is approximated by a group of experts in a systematic fashion based on past their experience.
6. *Default*. Often, a modeler will prepare a sample model application for demonstration purposes, and parameter values from these input files can be used.
7. *Best guess*. Sometimes, the only option is to guess at the value based on past experience and consultation with modelers and then use iterative modeling to calibrate the guess.

Technically, the author of each model should conduct an extensive sensitivity analysis of their model's parameters to identify each parameter's importance in order to avoid making detailed measurements or literature searches on minor parameters or using best guesses for the most important parameters.

Even the best historical data to estimate model parameters does not ensure simulations will have high accuracies or realism. There is always a tension between model design and model parameterization. Keane and others (2006), for example, found that fire regimes were simulated incorrectly when fire return interval parameters were quantified from tree fire scars located in topographic settings that experienced frequent fires, such as flat areas. The detail in the simulation model will never capture the detail of environmental factors that created the field evidence from which parameters are quantified. As a result of this complexity, it is difficult to realistically simulate disturbance or vegetation development without building overly complex models that are difficult to parameterize and inefficient to run for large landscapes over long simulation periods. As mentioned, it is important that results of any landscape simulation be compared with expert experience and any available data to determine if output is reasonable. If not, then the parameters should be adjusted to more closely approximate reality.

Initialization

Simulation Initialization

Quantification of site and stand initial values is also time-consuming and often costly to accomplish from landscape inventories. A scheme was devised in Keane and others (1996a) to assign information from a sampled stand to similar, unsampled stands. Site and stand parameter values were quantified using a potential vegetation approach where sites were classified to a "fire group" from topographical information provided by the GIS DEM (Fischer and Bradley 1987). Stand and site parameters that were not directly measured were quantified in the input file based on data taken from other studies or values in the literature for the fire group, such as fire return interval and fire size.

Real-world landscapes are climatologically, edaphically, and ecologically complex, to such a degree that they cannot be accurately represented in ecosystem process models because of time and computational constraints. The challenge

in initializing a study region for FireBGCv2 implementation is to define a set of initial characteristics that provide enough landscape detail to capture the driving ecological processes and disturbance patterns that influence the beginning of a simulation while not overwhelming system resources with detail that will ultimately be lost as the simulation proceeds. The first step in this process, and one that is critical in establishing a fieldwork sampling design, is to define a set of sites across the study region. Site boundaries should be established on the basis of similarity in soils and climatology—for example, using soils data from the State Soil Geographic (STATSGO) digital soils database or a biophysical landscape classification from the LANDFIRE Environmental Site Potential (ESP) layer. The ESP layer represents the vegetation type that could be supported within a given area based on its biophysical environment, and if aggregated to a coarse enough scale to eliminate sites smaller than about 5 percent of the simulation landscape, can approximate site boundaries. A suggested number of sites for a 50,000-ha simulation landscape is 8 to 12 (Figure 15). Site types in Figure 15 refer to a combination of dominant vegetation species, elevation, and climatology; for example, the ABLA/Low/Wet site is a relatively low-elevation, moist site that is dominated by subalpine fir forests.

Stand boundaries are defined on the basis of unique, existing, dominant vegetation types within a site. These types can be mapped using spatial data such as the LANDFIRE Existing Vegetation Type layer, stand inventory data, or other appropriately scaled land cover data layers. Stand structural characteristics such as overstory height can be incorporated into the stand classification using the LANDFIRE Existing Vegetation Height layer or other structural data layers. Integration of these data allows users to differentiate among stands characterized as having the same existing vegetation type but at different successional stages, perhaps as the result of a disturbance event. A simulation landscape that is 50,000 ha or more in area may contain 300 to 500 stands, depending on the complexity of the existing vegetation mosaic (Figure 16).

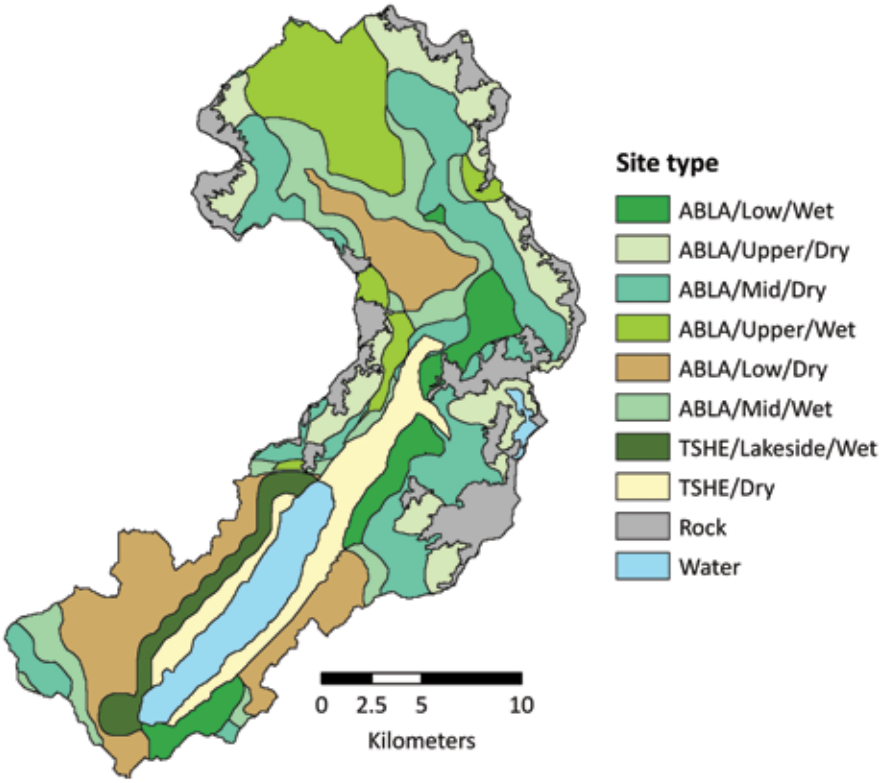

Figure 15. Site types mapped for the Lake McDonald area. "ABLA" represents subalpine fir, and "TSHE" represents western hemlock.

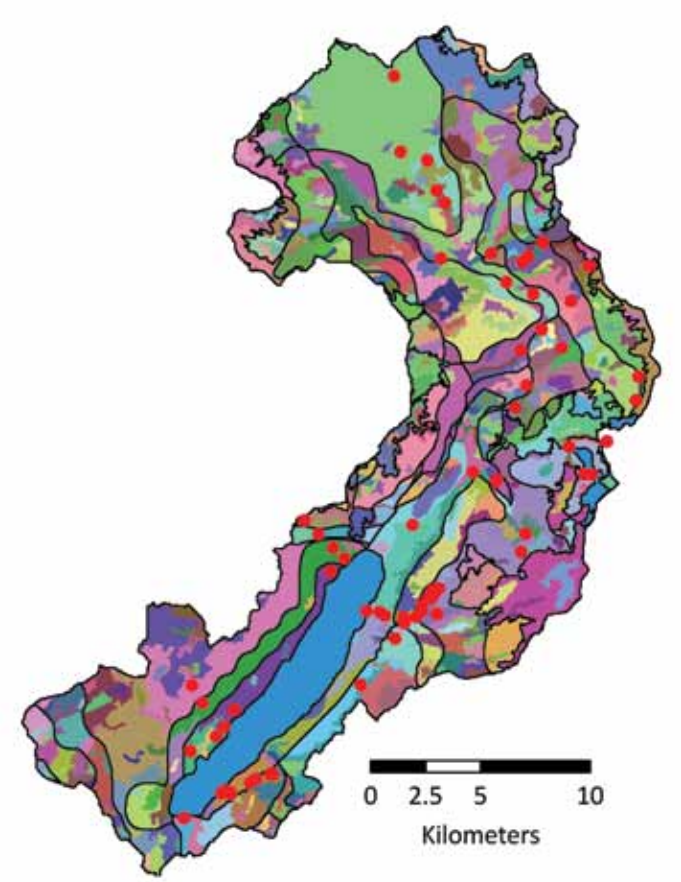

Figure 16. Stands mapped for the lake McDonald area. The red dots are field plots used to populate stand initial conditions. Black lines are the site boundaries, and each color represents a different stand vegetation type or structural stage.

Field sample plots should ideally be established within the study area so that each unique site-stand combination is sampled at least once. Figure 16 shows the location of field sampling plots within the McDonald watershed, Glacier National Park simulation area. Data from each plot are extrapolated across the simulation landscape to parameterize unsampled stands. Data collected within each simulation plot fall within three categories: (1) general plot description, including latitude and longitude; elevation; aspect; slope; plot area; plot-scale percent tree, shrub, and forb cover; dominant over- and understory vegetation species; stand height; and canopy cover; (2) vegetation data, including tree height; diameter; status; crown base height; and shrub and forb percent cover; and (3) fuels data, including 1 hr to 1000 hr fuel loadings and litter and duff bulk densities. Plot descriptive and vegetation cover field forms can be easily modified from those provided in the FIREMON Fire Effects Monitoring and Inventory System (Lutes and others 2006). The FIREMON reference also includes detailed information on data collection protocols and methods. We suggest using the FIREMON data collection protocols and forms because the system can be used to post-process field data to the format required for FireBGCv2 initialization.

A number of methods exist for estimating fuel loadings, including planar intersect techniques such as Brown's transects (Brown 1974), photo series (Sikkink and Keane 2008), and visual loading estimates such as the Photoload Sampling Technique (Keane and Dickinson 2007a, 2007b). The Photoload method uses calibrated, downward-looking photographs of known fuel beds as reference images for individual surface fuel beds. These reference loadings can be height- and volume-adjusted to match field observations. The Photoload method is well-suited for initialization of the fuel components of FireBGCv2 and includes sampling protocols and forms that can easily be modified to suit most sampling designs.

The field data types previously described, combined with site and stand spatial data layers, are used to build the Site.in, Stand.in, and vegetation and fuels input files described in the "Input File Structure" section. Together, these data comprise the initial conditions defined for a simulation landscape.

Model Initialization

Once the user has specified all the initial conditions using field data, the model then performs a number of initializations to populate the state variables. FireBGCv2 uses generalized tree input data taken from the Tree.in file to compute tree attributes needed in the simulation. Tree data are input to the model by stand from tables of tree density, diameter, height, height to base of crown, and age by species. The model creates a list of all trees in a stand from the tree density information and assigns the appropriate attributes (DBH, HT, HBC, and AGE) to the trees. Then, FireBGCv2 computes those attributes that are explicitly utilized by the model for each tree.

The tree's structural characteristics are computed first. The tree's ecophysiological compartment values are initialized first from allometric equations that use the input structural characteristics as independent variables. Leaf carbon (LeafC, kg C) is approximated from the Brown (1978) equations that estimate foliar biomass from DBH and species. This biomass estimate is then multiplied by the fraction of leaf biomass that is carbon. Leaf area is estimated from the product of the specific leaf area and LeafC (kg C). Stem carbon (LivestemC and DeadstemC, kg C) is estimated from the stem and bark volume equations of Faurot (1977) and crown volume equations of Brown (1978). Stem and bark volume, computed from DBH and HT, are multiplied by their respective densities and added together to obtain stem biomass. This biomass is then multiplied by the fraction that is carbon to estimate stem carbon. Coarse and fine root carbon (CrootC and FrootC, kgC) are estimated from the empirical biomass equations. The biomass estimates are multiplied by the fraction of that biomass that is carbon to obtain carbon in the coarse and fine roots. Tree nitrogen compartments are initially computed as proportions of the tree's corresponding carbon pools.

Most stand compartments are initialized from the sum of the corresponding tree compartments. Stand leaf area (LA, m^2) is the sum of leaf area for all trees and undergrowth. Leaf, stem, fine root, and coarse root carbon and nitrogen are the sum of the corresponding tree and undergrowth components. Some initial stand attributes are quantified from the stand input file. Snowpack (SnowW, kgW m^{-2}) and soil water (SoilW, kgW m^{-2}) also receive initial values from the Stand.in file. Starting values for all compartments that make up the ground or forest floor (see the "Ground Dynamics" section in "Stand Processes") and undergrowth (see the "Undergrowth Dynamics" in "Stand Processes") are obtained from the Stand. in file.

New estimates of some tree compartments are also computed at simulation year's end. A new tree leaf area is estimated from leaf carbon. Effective tree area and the resource allocation factor is recomputed from the new stand and tree leaf area estimates. Photosynthesis is initialized for the year at 10 percent of last year's net carbon gain to simulate the effect of carbon storage on the growth process (Running and Hunt 1993).

Calibration

Model calibration involves running the model under known and measureable conditions and generating results that are then compared against real data (that is hopefully collected from the landscape that is being simulated) to evaluate realism and accuracy. Rarely is there a dataset that can be used to properly calibrate a model because most inventories do not measure the response and explanatory variables output from the model. Here are some steps to take when calibrating the model:

1. Obtain all available data for the simulation landscape that can be used to evaluate model behavior. Possible data sources include:
   - Tree ring width data. These can be compared against model growth predictions.

- Stand development data. Any data that quantifies changes in stand structure for any stand(s) on the target landscape can be used to determine if the model is predicting stand development correctly.
- Fire history data. Maps of burn boundaries can be used to compute landscape fire rotation and to compute fire pattern metrics to compare against simulation results.
- Disturbance records. Any spatial or tabular records of disturbance impacts, such as mountain pine beetle damage, can be used to adjust or validate model output.
- Digital map chronosequences. Spatial layers that show the landscape at two or more time periods are especially useful for comparing modeled landscape changes to observed changes.

2. Craft a simulation scenario that best matches the collected data. This involves matching the initial conditions, site parameters (including weather), and tree lists to the conditions that are represented by the data.
3. Execute the model for a time period that matches the comparison data and output simulation variables that match those measured variables.
4. Use qualitative or statistical techniques to compare the results.
5. If results do not agree, adjust the appropriate parameters until results are compatible. For example, if not enough area burned on the landscape, then increase fire return intervals or fire size parameters in the Site.in file until results match. However, this is somewhat problematic, and it may take trial and error to figure out which parameters to adjust and how much to adjust them.
6. Keep repeating steps (3) through (5) until satisfied with comparison.

Simulation

This step involves executing the model for all the scenarios in the simulation experiment design. There are a few cautions in this process. FireBGCv2 produces copious results, especially if maps are requested as output, that tend to quickly fill hard disks, so be sure the computers have sufficient disk space. Second, FireBGCv2 requires abundant memory for long simulations, so it is best to have at least 6 to 10 gigabytes of memory available during the execution. Third, it is important that the simulation experiment be carefully designed to minimize confusion of results between scenarios. A directory structure should be created where files that do not change across scenarios, such as Fuel.in, Species.in, and Tree.in, are put in one directory, and files that will change across scenarios, specifically Sim.in, Map.in, and Climate.in, are placed in directories that represent the appropriate scenario. Output should also be stored in directory structure that emphasizes differences across scenarios. This directory structure can have many variations, and one useful variation is contained within this report (see the "Input File Structure" section).

It is actually quite easy to execute FireBGCv2 by simply entering the following command in a MS-DOS Command Prompt window:

C:>firebgcv2 driver.in

where *driver.in* is the name of the Driver.in input file that contains the filenames that drive the program. The *C:>* prompt indicates the directory in which to start the FireBGCv2 program. It is important that the program is started in a directory where the Driver.in files reside. So, if the files are in the directory c:\firebgc\yellowstone, then use the ***cd*** command and navigate to that directory by entering:

C:>cd c:\firebgc\yellowstone

Then the command prompt and FireBGCv2 execution command will be:

C:\ firebgc\yellowstone> firebgcv2 driver.in

The program will immediately begin printing messages on the status of the execution. You can shunt these messages to a file by using the following command:

C:\ firebgc\yellowstone> firebgcv2 driver.in > messagefile.txt

where *messagefile.txt* is a file that will store all of the messages generated from the program.

Output

FireBGCv2 provides many avenues for printing intermediate, non-spatial results during program execution. Model calculations can be printed to a variety of ASCII files depending on the temporal and organizational scale. These ASCII files can then be imported into statistical and graphic software packages for analysis and display. The model was programmed to allow the printout of additional variables with little or no modification of the program. All output file names are specified in the Driver.in file. The state and intermediate variables whose values are to be printed at the appropriate time step are specified in the Sim.in file. Any ecophysiological component at the stand and tree levels and any intermediate variable at the stand and tree levels can be printed to the appropriate files. This is done by specifying the index (*i*) of the compartment or intermediate variable in the output variable list (Table 7). A seasonal window is available to limit the printing of daily values to only a portion of the year. Only output data that are calculated for days between a specified starting and ending yearday, as entered in the Driver.in file, will be printed in the appropriate file. No data will be printed to any of the output files described next if the starting yearday for the seasonal window is entered as zero.

The first file created by FireBGCv2 is the Echo file that contains all input data and initialization data, as computed by the model (Echo.out). This file is used to verify that input file structure and data values are correct. The remaining output files are stratified by the time step at which they are updated (year or day) and the organizational scale described by the data (tree or stand).

Stand-level predictions for specified stand state variables, compartments, and intermediate variables, as specified in the Sim.in file, are printed each simulation day for every stand in the simulation into the Stand Day file (Stand.day). No tree-level predictions are printed at a daily time step. Each year, FireBGCv2 writes a number of computed values to the FireBGCv2 output files. Yearly tree output data are written to two files by FireBGCv2. The Tree List file (Tree.list) contains a list of trees by simulation year, site, and stand. Each tree is described by tree ID number, species acronym, DBH (cm), HT (m), and AGE (years). This variable list is also static and cannot be changed without FireBGCv2 program modification. The yearend values of the compartment and intermediate variables for a selected tree are written to the second tree output file, the Tree.year file. The target tree is specified by number in the Driver.in file. These yearly values are written for that same tree number across every stand in the simulation. No predictions are written for that tree once it dies.

Table 7. FireBGCv2 stand-level output variables that can be specified in the Sim.in file.

ID num	Variable name	Description	Units of measure
Tree silivicultural characteristics			
0	tree->age	Tree age	years
1	tree->carea	Tree crown area	m^2
2	tree->la	Tree leaf area	m^2
3	(DREAL)tree->stress	Number years of growth stress	years
4	(DREAL)tree->rust	Number of years infected by rust	years
Tree xt carbon state variables			
5	xt->leafC	Tree leaf carbon	kgC m^{-2}
6	xt->livestemC	Tree sapwood carbon	kgC m^{-2}
7	xt->deadstemC	Tree heartwood carb	kgC m^{-2}
8	xt->frootC	Tree fine root carb	kgC m^{-2}
9	xt->livecrootC	Tree live coarse root	kgC m^{-2}
10	xt->deadcrootC	Tree dead coarse root	kgC m^{-2}
11	xt->npp	Tree net primary prod	kgC m^{-2}
12	xt->psn	Tree photosynthesis	kgC m^{-2}
13	xt->respiration	Tree respiration	kgC m^{-2}
Stand ecosystem descriptive variables			
100	stand->fri	Fire return interval	years
101	stand->albedo	Stand albedo	dimensionless
102	stand->la	Stand leaf area	m^2
103	stand->lai	Stand allside LAI	dimensionless
104	stand->plai	Stand project LAI	dimensionless
105	stand->plaisun	Stand project LAI for sun leaves	dimensionless
106	stand->plaishade	Stand project LAI for shade leaves	dimensionless
107	stand->ba	Basal area	m^2 ha^{-1}
108	stand->ht	Ave stand height	m
109	stand->hbc	Ave stand height to crown	m
110	stand->cbd	Canopy bulk density crown	kg m^{-3}
111	stand->crown_area	Stand total crown area	m^2
112	stand->canopy_cover	Crown cover	percent
113	stand->area	Stand total area	ha
114	stand->nt	Stand number of trees	# trees
115	stand->nt_dead	Number of dead trees this year	# trees
116	ecostand->degree_days	Growing degree days	degrees C
269	stand->nt_sap	Number of new saplings this year	# trees
270	stand->nsnag	Stand number of snags	# snags
271	stand->ysf	Years since last fire	years
272	stand->pstage	Phenological stage	categorical
273	stand->lag	Years of lag after a fire	years
275	stand->habsuit1	Habitat suitability index	index
276	stand->habsuit2	Habitat suitability index	index
277	stand->habsuit3	Habitat suitability index	index
278	stand->habsuit4	Habitat suitability index	index
279	stand->habsuit5	Habitat suitability index	index
Stand ground variables			
250	ground->w1C	1 hour twigwood (0-1cm)	kgC m^{-2}
251	ground->w10C	10 hour twigwood (1-3cm)	kgC m^{-2}
252	ground->w100C	100 hour twigwood (3-8cm)	kgC m^{-2}
253	ground->w1000C	1000 hour twigwood (8+cm)	kgC m^{-2}
254	ground->leaffallC	Total leaffall carbon	kgC m^{-2}
255	ground->litterC	Total litter carbon	kgC m^{-2}
256	ground->duffC	Total duff carbon	kgC m^{-2}
257	xp->leafC	Leaf C	kgC m^{-2}
258	xp->frootC	Fine root C	kgC m^{-2}
259	xp->livestemC	Live stem C	kgC m^{-2}
260	xp->deadstemC	Dead stem C	kgC m^{-2}

Table 7. *Continued*.

ID num	Variable name	Description	Units of measure
Stand ground variables (*continued*)			
261	xp->livecrootC	Live coarse root C	kgC m^{-2}
262	xp->deadcrootC	Dead coarse root C	kgC m^{-2}
485	log_load	Dead coarse woody debris	kg m^{-2}
486	fuel_load	Dead fine woody debris	kg m^{-2}
487	duff_depth	Duff and litter depth	cm
488	stand->fbfmID	Fire behavior fuel model ID number	kgC m^{-2}
489	stemC	Tree stem carbon	kgC m^{-2}
490	shrubC	Shrub biomass	kgC m^{-2}
491	herbC	Herb biomass	kgC m^{-2}
Map variables			
263	sstage	Structural stage: seed, sap, pole	categorical
264	spp_ba	Species with greatest basal area	categorical
265	spp_la	Species with greatest leaf area	categorical
266	spp_dbh	Species with greatest diameters	categorical
267	spp_cover	Species with greatest cover	categorical
268	spp_biomass	Species with greatest biomass	categorical
Leaf dynamics			
650	ecostand->lai	Leaf area index	dimensionless
651	ecostand->plai	Projected leaf area index	dimensionless
652	ecostand->plaisun	Sunlit projected leaf area index	dimensionless
653	ecostand->plaishade	Shaded projected leaf area index	dimensionless
654	ecostand->sun_proj_sla	Sunlit projected SLA	m^2 kgC^{-1}
655	ecostand->shade_proj_sla	Shaded projected SLA	m^2 kgC^{-1}
656	ecostand->psn_sun	Sunlit assimilation per unit pLAI	umol m^{-2} s^{-1}
657	ecostand->psn_shade	Shaded assimilation per unit pLAI	umol m^{-2} s^{-1}
Soil variables			
658	ecostand->swf	Soil water fraction	dimensionless
659	ecostand->psi	Water potential of soil and leaves	-Mpa
660	ecostand->vwc	Volumetric water content	scalar
661	ecostand->gsws	Accumulated growing season water stress	-Mpa
662	ecostand->psi_max	Maximum annual leaf water potential	-Mpa
663	ecostand->psi_ave	Average annual leaf water potential	-Mpa
664	ecostand->swf_yr	Summation of soil water content	proportion
665	ecostand->soil_temp_yr	Soil temperature summation	degrees C
Water fluxes			
666	ecostand->rainW_thrufall	Rainfall reaching the forest floor	kgH2O m^{-2} day^{-1}
667	ecostand->rainW_drip	Rainfall drip from canopy not evaporated	kgH2O m^{-2} day^{-1}
668	ecostand->rainW_thrufall	Rainfall to soil water	kgH2O m^{-2} day^{-1}
669	ecostand->snowW_fall	Rainfall to snow water	kgH2O m^{-2} day^{-1}
670	ecostand->rainW_intercepted	Rainfall captured by leaves—intercepted	kgH2O m^{-2} day^{-1}
671	ecostand->snowW_fall	Snowfall	kgH2O m^{-2} day^{-1}
672	ecostand->snowW_melt	Snowmelt	kgH2O m^{-2} day^{-1}
673	ecostand->snowW_sub	Snow sublimation	kgH2O m^{-2} day^{-1}
674	ecostand->snowW_melt	Snow water to soil water	kgH2O m^{-2} day^{-1}
675	ecostand->soilW_evap	Evaporation of water from soil	kgH2O m^{-2} day^{-1}
676	ecostand->soilW_outflow	Soil water lost to runoff and ground water	kgH2O m^{-2} day^{-1}
677	ecostand->soilW_trans	Soil water transpired by canopy	kgH2O m^{-2} day^{-1}
678	ecostand->canopyW_drip	Evaporation of water from canopy	kgH2O m^{-2} day^{-1}
679	ecostand->canopyW_trans	Canopy transpiration	kgH2O m^{-2} day^{-1}
680	ecostand->canopyW_evap	Canopy evaporation	kgH2O m^{-2} day^{-1}
681	ecostand->transW	Water transpired by canopy	kgH2O m^{-2} day^{-1}

Table 7. *Continued.*

ID num	Variable name	Description	Units of measure
Evapotranspiration variables (conductances and multipliers)			
682	ecostand->et	Evapotranspiration	kg m^{-2}
683	ecostand->pet	Potential evapotranspiration	kg m^{-2}
684	ecostand->ppfd_per_plaisun	PPFDensity per PLAI sunleaves	dimensionless
685	ecostand->ppfd_per_plaishade	PPFDensity per PLAI sunleaves	dimensionless
686	ecostand->m_tmin	Freezing night temperature multiplier	dimensionless
687	ecostand->m_psi	Water potential multiplier	dimensionless
688	ecostand->m_co2	Atmospheric [CO2] multiplier	dimensionless
689	ecostand->m_ppfd_sun	PAR flux density multiplier	dimensionless
690	ecostand->m_ppfd_shade	PAR flux density multiplier	dimensionless
691	ecostand->m_vpd	Vapor pressure deficit multiplier	dimensionless
692	ecostand->m_final_sun	Product of all other multipliers for sunlit	dimensionless
693	ecostand->m_final_shade	Product of all other multipliers for shaded	dimensionless
694	ecostand->gl_bl	Leaf boundary layer conductance	m s^{-1}
695	ecostand->gl_c	Leaf cuticular conductance	m s^{-1}
696	ecostand->gl_s_sun	Leaf-scale stomatal conductance	m s^{-1}
697	ecostand->gl_s_shade	Leaf-scale stomatal conductance	m s^{-1}
698	ecostand->gl_e_wv	Leaf conductance to evaporated water	m s^{-1}
699	ecostand->gl_sh	Leaf conductance to sensible heat	m s^{-1}
700	ecostand->gl_t_wv_sun	Leaf cond to water vapor sunlit leaves	m s^{-1}
701	ecostand->gl_t_wv_shade	Leaf cond to water vapor shaded leaves	m s^{-1}
702	ecostand->gc_e_wv	Canopy conductance to evaporated water	m s^{-1}
703	ecostand->gc_sh	Canopy conductance to sensible heat	m s^{-1}
704	ecostand->gcorr	Conductance correction factor	scalar
Respiration variables			
705	ecostand->mr_leaf	Daily leaf respiration—night and day	kgC day^{-1}
706	ecostand->mr_leafC_day	Daytime leaf respiration	kgC day^{-1}
707	ecostand->mr_leafC_night	Nighttime leaf respiration	kgC day^{-1}
708	ecostand->mr_lstemC	Sapwood respiration assumes only sapwood live	kgC day^{-1}
709	ecostand->mr_lcrootC	Coarse root respiration	kgC day^{-1}
710	ecostand->mr_frootC	Fine root respiration	kgC day^{-1}
711	ecostand->dlmr_area_sun	Sunlit leaf MR	umolC m^{-2} projected leaf area s^{-1}
712	ecostand->dlmr_area_shade	Shaded leaf MR	umolC m^{-2} projected leaf area s^{-1}
713	ecostand->n_area_sun	Mass Nitrogen per unit proj leaf area sunlight	kgN m^{-2}
714	ecostand->n_area_shade	Mass Nitrogen per unit proj leaf area shade	kgN m^{-2}
715	ecostand->leafC_max	Maximum Leaf carbon in stand	kgC
716	ecostand->can_leafN2can	Canopy nitrogen as percent of max canopy N	proportion
717	ecostand->leafN_conc	Canopy leaf N concentration	kgN kgC^{-1}
718	ecostand->leafN_trans	Canopy leaf N retranslocation fraction	scalar 0 to 1
719	ecostand->leaf_long	Leaf retention time	years
720	ecostand->leaf_falltolitC	Leaffall contribution to litter carbon	kgC
Diagnostic variables			
721	ecostand->ytd_maxplai	Year-to-date maximum projected LAI	m^2 m^{-2}
722	ecostand->npp	Net Primary Productivity = GPP - Rmaint - Regrowth	kgC m^{-2} day^{-1}
723	ecostand->nep	Net Ecosystem Production = NPP - Rheterotroph	kgC m^{-2} day^{-1}
724	ecostand->nee	Net Ecosystem Exchange = NEP - fire losses	kgC m^{-2} day^{-1}
725	ecostand->gpp	Gross Primary Productivity = PSN source	kgC m^{-2} day^{-1}
726	ecostand->mr	Maintenance respiration	kgC m^{-2} day^{-1}
727	ecostand->gr	Growth respiration	kgC m^{-2} day^{-1}
728	ecostand->hr	Heterotrophic respiration	kgC m^{-2} day^{-1}
729	ecostand->fireC	Fire carbon losses	kgC m^{-2} day^{-1}
730	ecostand->vegC	Total vegetation C	kgC m^{-2}
731	ecostand->litC	Total litter C	kgC m^{-2}
732	ecostand->soilC	Total soil C	kgC m^{-2}
733	ecostand->totalC	Total of vegC, litrC, and soilC	kgC m^{-2}

Table 7. *Continued*.

ID num	Variable name	Description	Units of measure
Diagnostic variables (*continued*)			
734	ecostand->sum_npp	Summed over entire simulation	kgC m^{-2}
735	ecostand->sum_nep	Summed over entire simulation	kgC m^{-2}
736	ecostand->sum_nee	Summed over entire simulation	kgC m^{-2}
737	ecostand->sum_gpp	Summed over entire simulation	kgC m^{-2}
738	ecostand->sum_mr	Summed over entire simulation	kgC m^{-2}
739	ecostand->sum_gr	Summed over entire simulation	kgC m^{-2}
740	ecostand->sum_hr	Summed over entire simulation	kgC m^{-2}
741	ecostand->sum_fire	Summed over entire simulation	kgC m^{-2}
Decomposition and accumulation variables			
742	ecostand->leafC_to_leaffallC	Leaf carbon to leaffall carbon	kgC m^{-2}
743	ecostand->leaffallC_to_litterC	Leaf carbon to litter carbon (gap)	kgC m^{-2}
744	ecostand->dstemC_to_w1C	Stem carbon to 1 hr woody carbon (gap)	kgC m^{-2}
745	ecostand->dstemC_to_w10C	Stem carbon to 10 hr woody carbon (gap)	kgC m^{-2}
746	ecostand->dstemC_to_w100C	Stem carbon to 100 hr woody carbon (gap)	kgC m^{-2}
747	ecostand->dstemC_to_cwd	Stem carbon to 1000 hr woody carbon (gap)	kgC m^{-2}
748	ecostand->litterC_to_duffC	Litter carbon to duff carbon (gap)	kgC m^{-2}
749	ecostand->duffC_to_soilC	Duff carbon to soilC or sink (gap)	kgC m^{-2}
750	ecostand->w1C_to_duffC	Woody 1 hr carbon to duff carbon	kgC m^{-2}
751	ecostand->w10C_to_duffC	Woody 10 hr carbon to duff carbon	kgC m^{-2}
752	ecostand->w100C_to_duffC	Woody 100 hr carbon to duff carbon	kgC m^{-2}
753	ecostand->w1000C_to_duffC	Woody 1000 hr carbon to duff carbon	kgC m^{-2}
754	ecostand->w1C_to_soilC	Woody 1 hr carbon to soil carbon	kgC m^{-2}
755	ecostand->w10C_to_soilC	Woody 10 hr carbon to soil carbon	kgC m^{-2}
756	ecostand->w100C_to_soilC	Woody 100 hr carbon to soil carbon	kgC m^{-2}
757	ecostand->w1000C_to_soilC	Woody 1000 hr carbon to soil carbon	kgC m^{-2}
Grab-bag of variables added at a later date			
758	ecostand->npp	Species-level NPP estimate	kgC m^{-2}
760	ecostand->annoutflow	Water lost from the site	kgH2O m^{-2} $year^{-1}$
Carbon summary variables			
722	ecostand->npp	Net Primary Productivity = GPP - Rmaint - Regrowth	kgC m^{-2}
723	ecostand->nep	Net Ecosystem Production = NPP - Rheterotroph	kgC m^{-2}
724	ecostand->nee	Net Ecosystem Exchange = NEP - fire losses	kgC m^{-2}
725	ecostand->gpp	Gross Primary Productivity = PSN source	kgC m^{-2}
726	ecostand->mr	Maintenance respiration	kgC m^{-2}
727	ecostand->gr	Growth respiration	kgC m^{-2}
728	ecostand->hr	Heterotrophic respiration	kgC m^{-2}
770	ecostand->abovegroundC	Standing crop of aboveground C	kgC m^{-2}
771	ecostand->groundC	All dead biomass on the ground	kgC m^{-2}
772	ecostand->deadC	Aboveground dead carbon	kgC m^{-2}
773	ecostand->liveC	Aboveground live carbon	kgC m^{-2}
774	ecostand->fireC	Fire carbon losses	kgC m^{-2}
775	ecostand->litC	Total litter C	kgC m^{-2}
776	ecostand->snagC	Total snag C	kgC m^{-2}
777	ecostand->soilC	Total soil C	kgC m^{-2}
778	ecostand->totalC	Total of all carbon on site	kgC m^{-2}

Demonstration

This section presents example graphical (output maps) and tabular (output files) output from the FireBGCv2 model. The simulation landscape presented is the Lake McDonald watershed in Glacier National Park, Montana, USA (Figure 17). Simulation specifics are an historical weather scenario with no fire suppression (all fires allowed to burn) and no management actions (no clearcutting, thinning, or prescribed burning) implemented on the landscape. All model input files and parameters are quantified for the Lake McDonald landscape (Keane and others 1996a). The following simulation specifications (as defined in the Sim.in file) apply: succession model driver = mechanistic gap model; simulation time = 500 years; fire spread model = LANDSUM; fire ignition probability = site-level fire return intervals; and phenology = dynamic phenology model.

The Lake McDonald simulation landscape is an approximately 50,000-ha watershed on the western slope of the Continental Divide. Elevation within the watershed ranges from 950 m at lakeside locations to 2900 m in alpine areas. Approximately 75 percent of the watershed is forested, predominantly in coniferous types such as western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*), and lodgepole pine (*Pinus contorta*). Two distinct fire regimes are present in the watershed: large, stand-replacement fires on moist sites with fire return intervals of 120 to 350 years; and mixed-severity fires in drier areas with fire return intervals of 25 to 75 years. The species and their parameterizations are shown in Table 8. Lake McDonald site types (Figure 15) and stands (Figure 16) were mapped using data layers from the LANDFIRE project.

As with any research tool, the types of analyses performed and output created should be question-driven and represent the most parsimonious and straightforward method of presenting research results. Unlike many other models, FireBGCv2 offers users a broad array of potential output variables and types, and the following sample output is not meant to be inclusive of all output variables and data types.

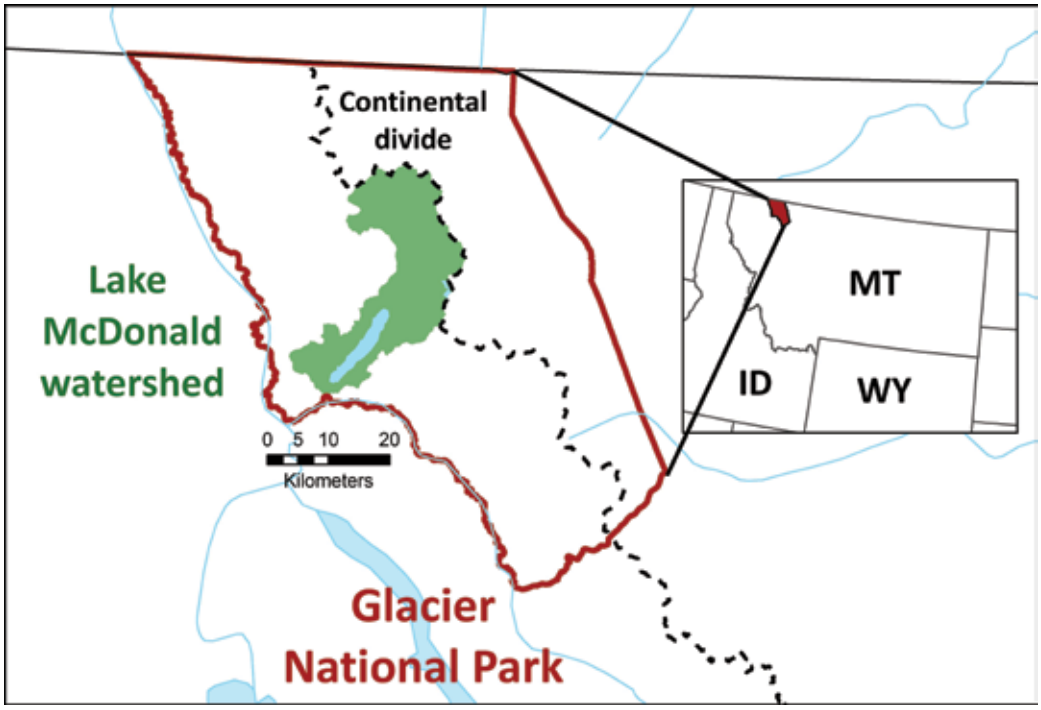

Figure 17. Lake McDonald watershed simulation landscape, Glacier National Park, Montana, USA.\

Table 8. FireBGCv2 species input parameters for the McDonald drainage in Glacier National Park.

Parameters	UNITS	Ponderosa pine	Grand fir	Douglas -fir	Lodgepole pine	Western larch	Subalpine fir	Engelmann spruce	Whitebark pine	Alpine larch	Western white pine	Western red cedar	Western hemlock	Quaking aspen	Paper birch
Species name in four-letter alpha code		**PIPO**	**ABGR**	**PSME**	**PICO**	**LAOC**	**ABLA**	**PIEN**	**PIAL**	**LALY**	**PIMO**	**THPL**	**TSHE**	**POTR**	**BEPA**
Species ID number		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Vegetation lifeform	(0-evergreen, 1-deciduous, 2-shrub, 3-grass)	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Shade Tolerance Class	(1-vsi, 2-si, 3-mst, 4-st, 5-vst)	1	4	4	2	1	4	4	2	1	2	4	5	1	1
Sprouting ability	(0-none, 1-low, 2-moderate, 3-prolific)	0	0	0	0	0	0	0	0	0	0	0	0	1	3
Rain interception coefficient	(1/LAI/day)	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.001	0.001
Light extinction coefficient	dimensionless	0.35	**0.45**	0.45	0.3	0.312	0.45	0.45	0.35	0.312	0.4	0.5	0.5	0.5	0.5
All-sided-to-projected conversion factor	dimensionless	3.54	2.04	2.85	3.54	3.54	2.04	2.94	3.54	3.54	3.54	2.8	2.8	2	2
SapwoodC to deadwoodC ratio	dimensionless	0.9	0.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Specific leaf area of a projected area basis	m^2 kg C^{-1}	20	25	22.8	21.9	18	20	20	21	16	25	20	20	25	25
Ratio of shade to sunlit SLA	dimensionless	1	2	2.0	1	1	3	2	1	1	1	3	3	1	1
Fraction of leaf N in Rubisco	dimensionless	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Maximum canopy conductance (gmax)	m sec^{-1}	0.0065	0.0065	0.0067	0.006	0.006	0.0065	0.0064	0.0067	0.0067	0.006	0.006	0.006	0.003	0.003
Leaf cuticular conductance (gc)	m sec^{-1}	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
Leaf boundary layer conductance (gb)	m sec^{-1}	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Leaf water potential at field capacity	-Mpa	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Leaf water potential at stomatal closure	-Mpa	-1.65	-1.4	-1.6	-1.46	-1.5	-1.4	-1.3	-1.65	-1	-1.5	-1.3	-1.3	-2.3	-2.3
Min vapor pressure deficit to affect conduct	Pa	500	500	700	500	500	500	500	500	500	500	500	500	1000	1000
Max vapor pressure deficit to affect conduct	Pa	2000	2000	3500	2000	2000	2000	2000	2000	2000	2000	2000	2000	4200	4200
Light compensation point	W/m^2	560	300	400	550	550	350	370	540	600	450	300	250	550	550
Carbon:Nitrogen (C:N) ratio for live leaves	dimensionless	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Critical litter C:N ratio	dimensionless	93	93	93	93	93	93	93	93	93	93	93	93	93	93
Critical fine root C:N ratio	dimensionless	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Live wood C:N ratio	dimensionless	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Dead wood C:N ratio	dimensionless	729	729	729	729	729	729	729	729	729	729	729	729	729	729
Critical duff C:N ratio	dimensionless	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Leaf and fine root turnover fraction	kgC $kgC^{-1}year^{-1}$	0.33	0.2	0.25	0.25	1	0.2	0.2	0.17	1	0.33	0.25	0.25	1	1
Live wood turnover fraction	kg C kg C^{-1}	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.75	0.75	0.7	0.7	0.7	0.75	0.75
Stem, branch, and coarse root turnover fraction	kg C kg C^{-1}	0.04	0.09	0.01	0.05	0.05	0.1	0.1	0.05	0.05	0.1	0.1	0.1	0.05	0.05
New fine root C to new leaf C allocation	dimensionless	1	1	1	1	1	1	1	1	1	1	1	1	1	1
New stem C to new leaf C allocation	dimensionless	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
New live wood C to new total wood C allocation	dimensionless	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
New coarse root C to new stem wood C allocation	dimensionless	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Current growth to storage C allocation	dimensionless	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 8. *Continued.*

Parameters	UNITS	Ponderosa pine	Grand fir	Douglas -fir	Lodgepole pine	Western larch	Subalpine fir	Engelmann spruce	Whitebark pine	Alpine larch	Western white pine	Western red cedar	Western hemlock	Quaking aspen	Paper birch
Species name in four-letter alpha code		**PIPO**	**ABGR**	**PSME**	**PICO**	**LAOC**	**ABLA**	**PIEN**	**PIAL**	**LALY**	**PIMO**	**THPL**	**TSHE**	**POTR**	**BEPA**
Proportion C to allocate to indiv tree leafC	(DIM)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Leaf labile carbon fraction	kg lab C kgC^{-1}	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Leaf cellulose carbon fraction	kg cell C kgC^{-1}	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Leaf lignin fraction	kg ligninC kgC^{-1}	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Fine root labile carbon fraction	kg lab C kgC^{-1}	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fine root cellulose carbon fraction	kg cell C kgC^{-1}	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Fine root lignin fraction	kg ligninC kgC^{-1}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wood cellulose carbon fraction	kg cell C kgC^{-1}	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Wood lignin fraction	kg ligninC kgC^{-1}	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Maximum attainable age	years	650	275	350	220	450	180	320	1000	800	350	650	650	120	120
Maximum attainable height	m	65.63	53.7	57.15	41.15	68.58	41.76	54.56	36.57	30.48	56	79	79	35	35
Maximum attainable diameter	cm	250.5	139.4	208.84	110	250	126.7	234.4	182	168	254	300	300	130	130
Minimum number degree days	degree days (degC)	1350	1200	988	988	991.9	427.7	527.4	426.7	426.7	1200	1350	1350	260	1000
Optimum number degree days	degree days (degC)	1750	1650	1650	1650	1650	1400	1400	1000	1000	1650	1750	1750	1371	1650
Maximum number degree days	degree days (degC)	4767.4	3979	3979	3500	3979	3426.7	3426.7	2871	2871	3593	4000	4000	3000	3979
Minimum threshold on water stress curve	ratio	0.15	0.37	0.22	0.28	0.28	0.55	0.59	0.23	0.65	0.28	0.4	0.5	0.1	0.4
Site index at 50 years	m	14	10	13	10	15	8	11	9	8	16	12	14	6	6
Probability of good cone crop	probability	0.395	0.333	0.446	0.318	0.438	0.333	0.167	0.8	0.368	0.318	0.25	0.33	0.368	0.368
Proportion of seeds in serotinous cones	proportion	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0
Reproductive age	years	20	15	20	15	15	25	25	60	50	15	20	20	15	15
Minimum diameter growth increment	cm	0.012	0.005	0.007	0.015	0.016	0.008	0.008	0.006	0.007	0.016	0.005	0.005	0.016	0.016
Survival by duff depth—alpha coefficient	probability	10.59	40.01	38.69	14.12	20.17	40.01	40.01	40.01	40.01	40.01	40.01	40.01	20.17	20.17
Survival by duff depth—beta coefficient	probability cm^{-1}	2.74	5.115	4.24	2.28	5.59	6.115	6.115	6.115	6.115	6.115	6.115	6.115	5.59	5.59
Bark thickness coefficient	cm bark cm DBH^{-1}	0.063	0.046	0.063	0.028	0.063	0.015	0.022	0.03	0.05	0.035	0.035	0.05	0.014	0.021
Initial live crown fraction for mature trees	m m^{-1}	0.4	0.8	0.8	0.4	0.4	0.8	0.8	0.5	0.45	0.4	0.8	0.8	0.4	0.4
Establishment age	years	15	10	15	10	7	25	25	30	27	15	30	30	7	7
Establishment live crown ratio	m m^{-1}	0.5	0.8	0.6	0.5	0.4	0.8	0.6	0.4	0.4	0.4	0.8	0.8	0.4	0.4
Establishment height	m	1.4	1.5	1.4	1.4	1.8	1.5	1.5	1.5	1.4	1.8	1.5	1.5	1.8	1.8
Leaf start date or leaf out day	yearday	0	0	0	0	115	0	0	0	0	0	0	0	140	140
Leaf drop date	yearday	366	366	366	366	280	366	366	366	366	366	366	366	245	245
Time for leaf drop or growth	days	10	10	13	10	15	18	11	9	8	16	12	14	6	6
Latest tolerable spring frost	yearday	120	160	160	200	170	210	211	220	220	180	150	150	170	170
Earliest tolerable autumn frost	yearday	230	230	210	200	210	220	220	230	220	220	260	260	210	210
Average snag life	years	20	20	30	20	40	20	30	90	90	20	20	20	20	20

Graphical Output

Graphical model output consists of thematic maps that are created at user-defined intervals (as specified in the Sim.in file) for specific annual, stand-level variables specified in the Map.in file. The model defines 20 variables for thematic output, including dominant species by basal area, cover type, leaf area, DBH, and biomass; structural stage, stand age, and stand LAI; cumulative number of fires; and gross primary, net primary, and net ecosystem productivity. Maps are output in ASCII format and can be converted into GIS raster layers using geoprocessing software such as ESRI ArcMap. Geoprocessing software can also be used for post-processing and analysis of raster layers. For example, GIS software can be used to strip away a buffer area from around the simulation landscape, to aggregate thematic data across multiple simulation runs, or for change detection across simulation time steps.

Figures 18 and 19 show straightforward visualization of thematic output for two variables—dominant species by percent cover within each stand (sppIDcov in Map.in; Figure 18) and cumulative number of fires (fireatls in Map.in; Figure 19)—at 50-year simulation time steps for a 500-year simulation period. These map layers display output data for a single FireBGCv2 run; there

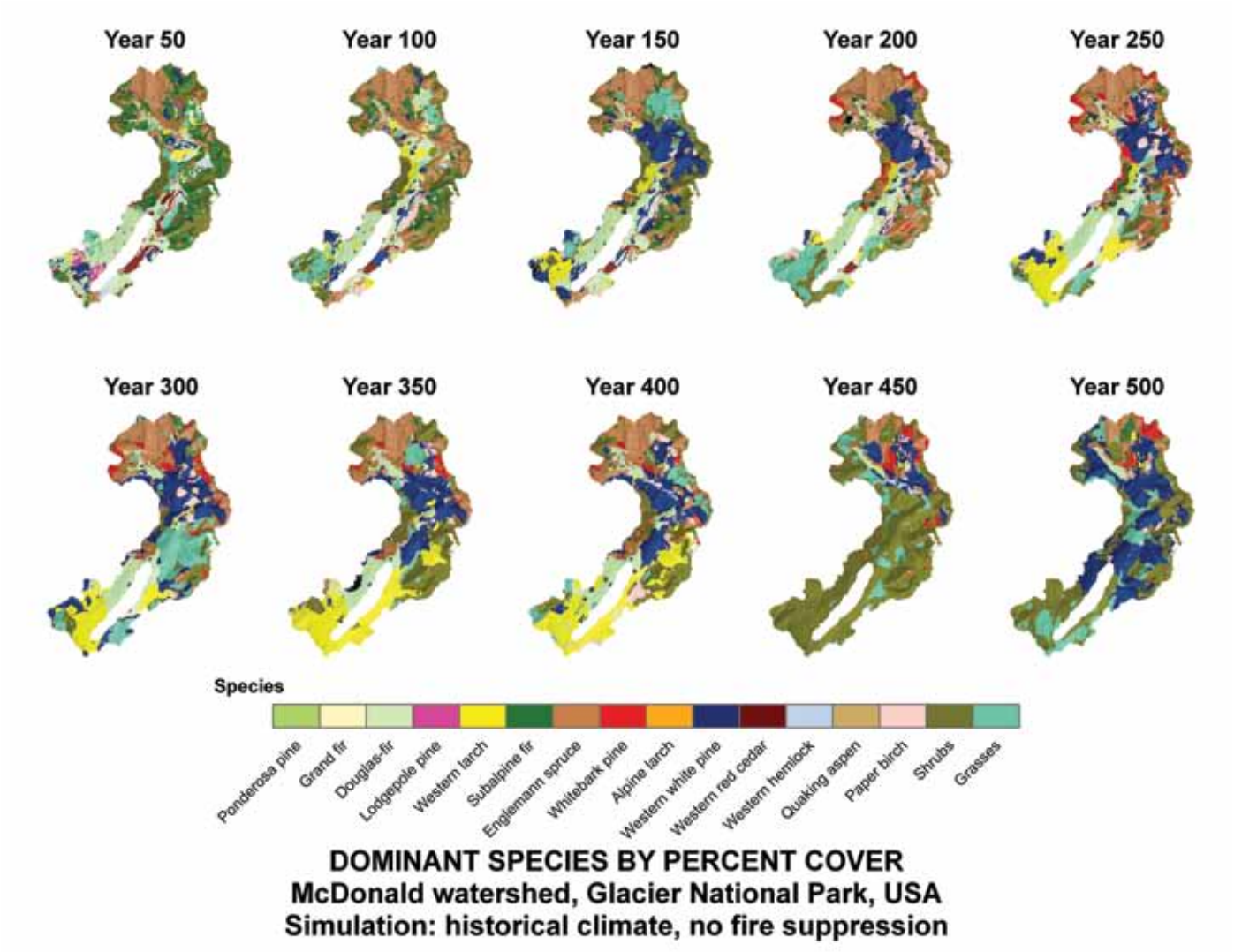

Figure 18. Dominant species by percent cover at 50-year intervals, 500-year simulation, Lake McDonald watershed, Glacier National Park, USA.

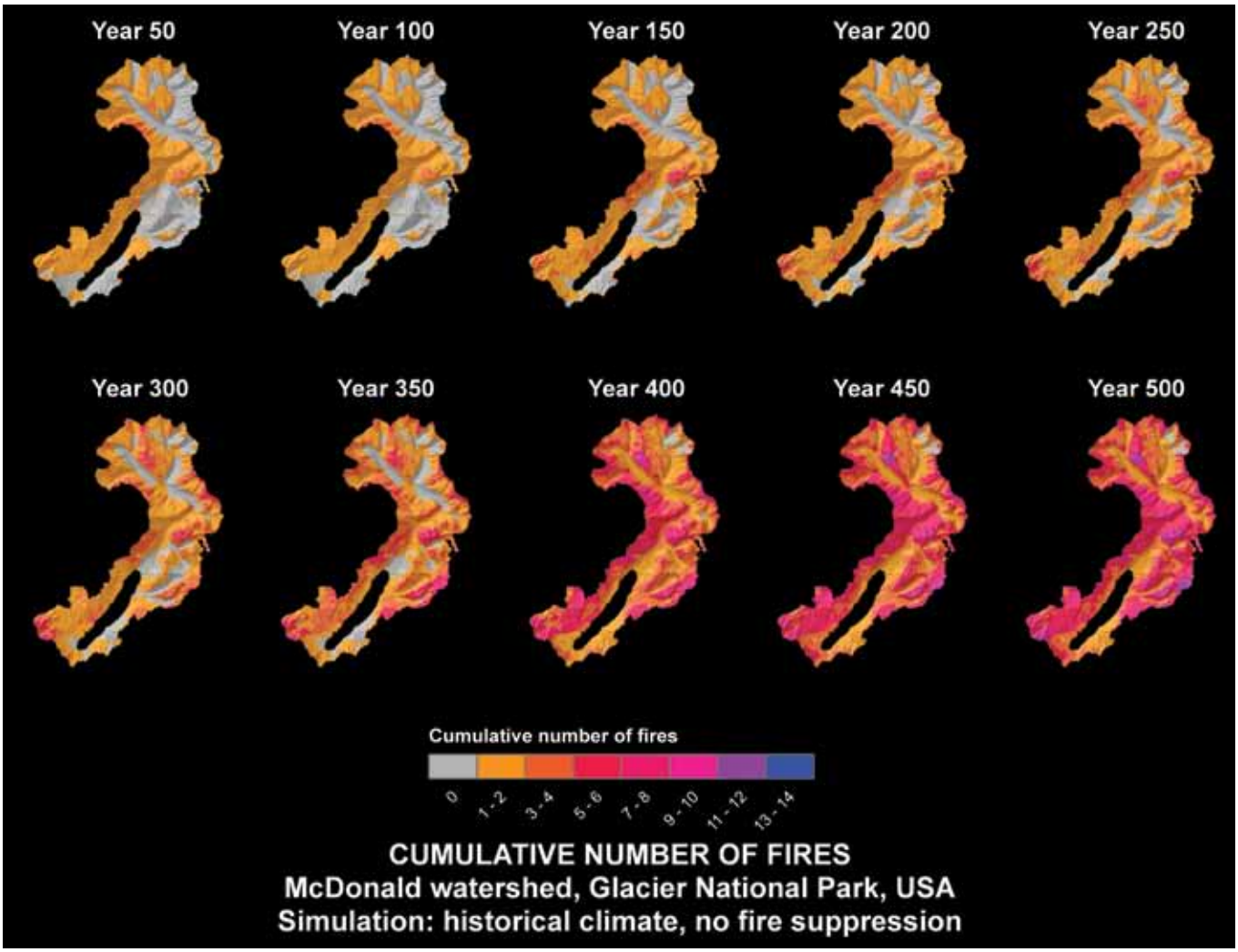

Figure 19. Cumulative number of fires at 50-year intervals, 500-year simulation, Lake McDonald watershed, Glacier National Park, USA.

has been no statistical or numerical aggregation of the data across multiple replicate runs. Simple graphical outputs can be very useful for model calibration, in which ecosystem processes and patterns are examined for internal consistency. For example, in Figures 18 and 19, stands that experienced frequent fires, as indicated by a high cumulative number of fires across the simulation period, show significant shifts in vegetation species composition as compared with stands in which few fires burned over 500 years. Specifically, fire-dependent, seral species such as western larch (*Larix occidentalis*) and western white pine (*Pinus monticola*) increase in prominence across stands following wildfire, while fire-sensitive species such as Englemann spruce (*Picea engelmanni*) and subalpine fir (*Abies lasiocarpa*) disappear in frequently burned stands. Similarly, wildfires can result in short- or long-lived transitions to grasses or shrubs, especially under potential climate warming scenarios.

Figure 20 illustrates post-processed map layers that display information not directly available in the primary graphical output layers. The uppermost panels show stand composition in forest or shrub- and grassland for simulation years 100 and 500, developed through a reclassification scheme of vegetation species (including shrubs and grasses) present on the simulation landscape at each time step. Data in these panels represent median values for each pixel across five replicate

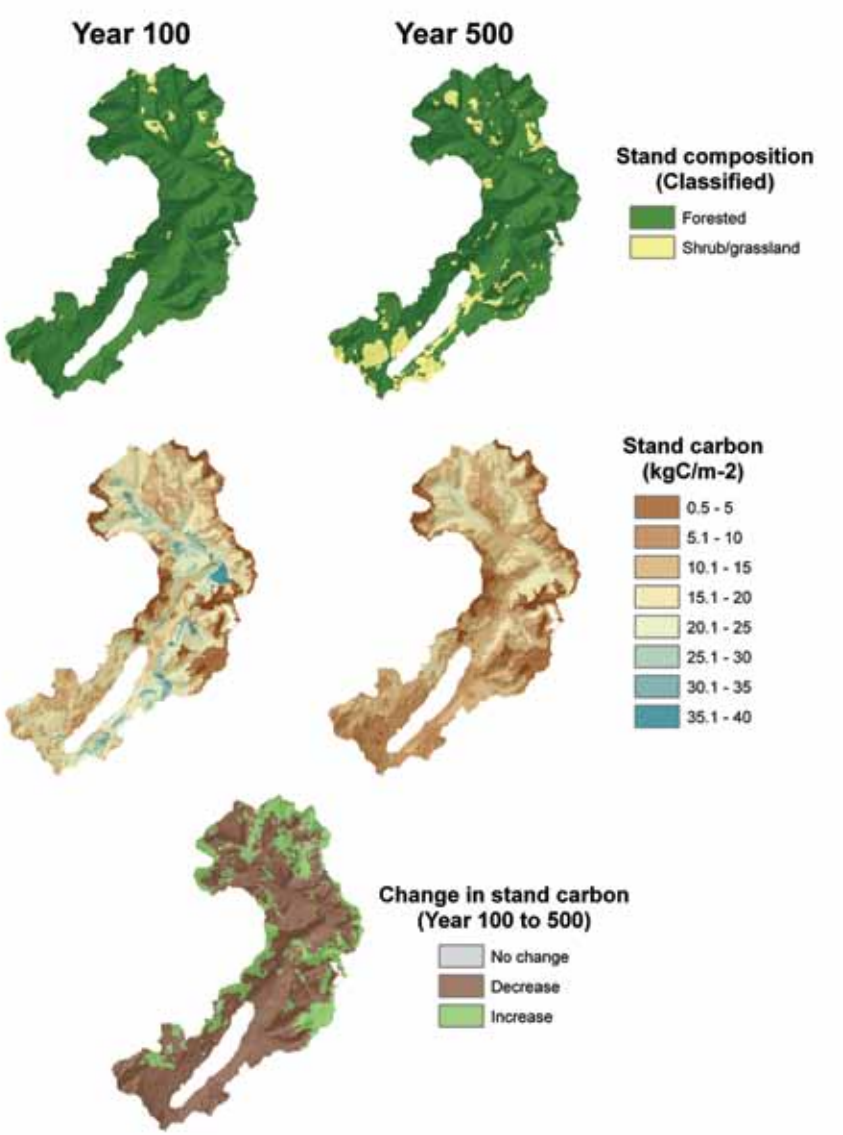

Figure 20. Stand composition in forest or shrub- and grassland (Upper) and mean values for stand carbon (Middle) for simulation years 100 and 500; and change in stand carbon from simulation years 100 to 500 (Lower), Lake McDonald watershed, Glacier National Park, USA.

model runs. The middle panels show mean values for stand carbon for each pixel across five replicate model runs. In the lower panel, a differencing algorithm has been used to produce a single map layer that shows the categorical change in stand carbon (increase, decrease, or no change) from simulation years 100 to 500, using the data layers in the middle panels as inputs.

Tabular Output

Tabular model output consists of horizontally arrayed ASCII flat files that contain values for tree- and stand-level variables, wildfires, and landscape-level carbon summations. There are currently more than 200 stand-level variables that can be summarized at annual time scales, including dominant species by basal area, cover type, leaf area, and biomass (Table 7). Stand-level variables are selected for output in the Sim.in file, and output file pathnames and prefixes are specified in the Driver.in file. As with graphical output, the choice of output variables should be question-driven to limit model processing time and file size.

The envelope-style graphs in Figure 21 show minimum (lower envelope bound), maximum (upper envelope bound), and mean (dashed line) values across five replicate simulations for proportion of the simulation landscape area occupied by mature versus sapling trees (Top) and western larch, subalpine fir, and western

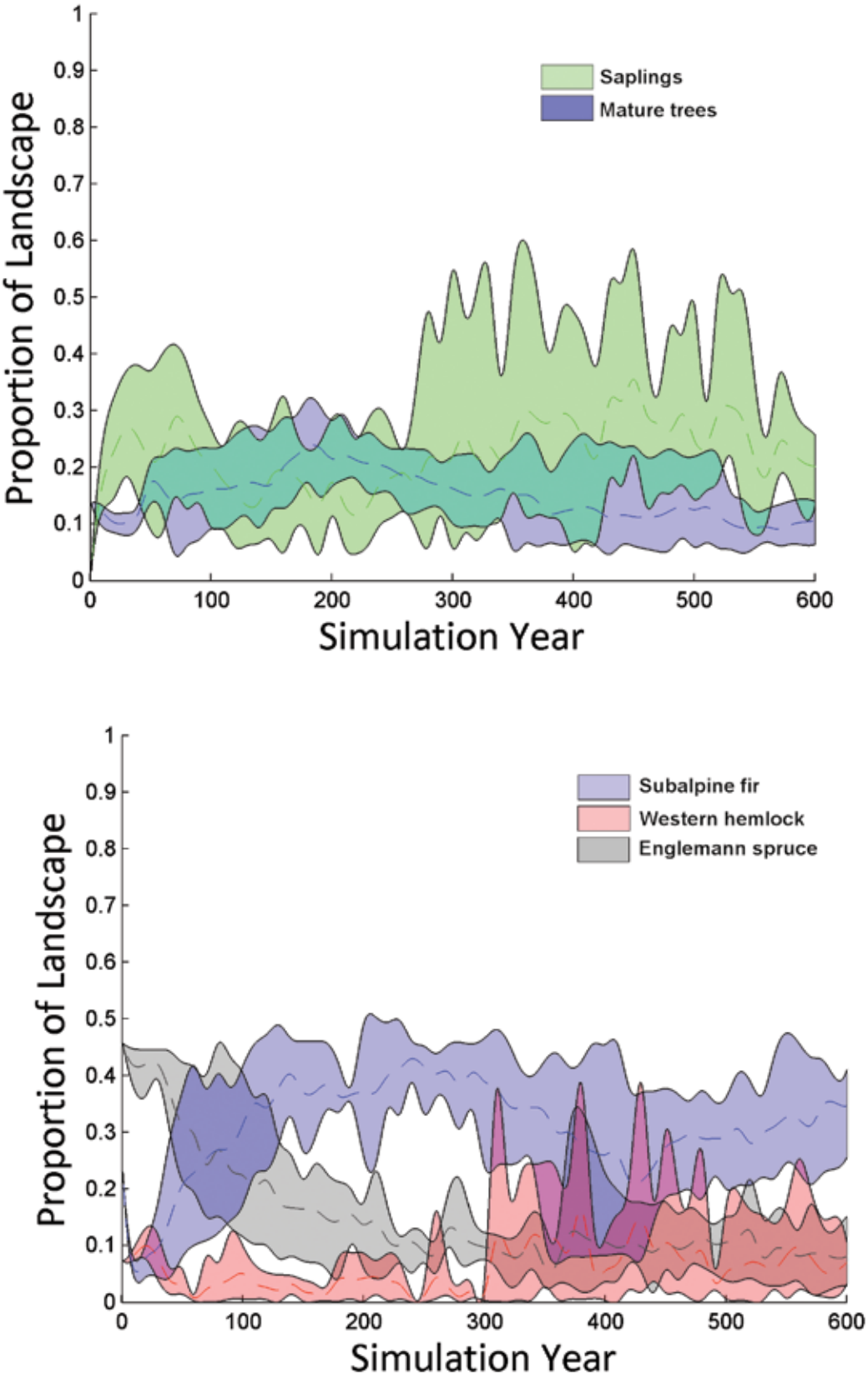

Figure 21. Minimum (lower envelope bound), maximum (upper envelope bound), and mean (dashed line) proportion of the simulation landscape area occupied by mature versus sapling trees (Top); and western larch, subalpine fir, and western hemlock (Bottom).

hemlock (Bottom). These graphs illustrate change in model variables across the simulation period and also quantify the variability among replicate simulations. As with the graphical output previously described, shifts in prominence of vegetation species are likely associated with changing patterns of wildfire disturbance, in which repeated fire events on the landscape decrease the proportion of fire-sensitive subalpine fir and favor establishment of fire-adapted western larch. Similarly, an increase in the proportional area occupied by immature (sapling) trees may reflect stand initiation following disturbance events. Figure 22 shows another display method for structural stage output data, in which stages (seedling, sapling, pole, mature, large, and very large) are shown as percent of the simulation landscape at simulation years 100, 250, and 500. As with the envelope graphs, changes in structural stages reflect successional processes influenced by disturbance events, climate variability, and species interactions.

Landscape fire and carbon information can be assessed through tabular output in the Stand.fire and Land.year output files. For example, the Stand.fire output file provides information on number of fires, fire size per site and stand, and total area burned during each simulation year (Figure 23). These data can be used to compare wildfire dynamics across simulation replicates to assess model variability, recognize underlying driving processes in the model (for example, fire return intervals at site and simulation landscape scales), and understand relationships among disturbance events and ecosystem processes such as succession, net primary productivity, or landscape carbon dynamics. The Land.year output file contains landscape-scale carbon data for each simulation year, including emissions from wildfires and autotrophic and heterotrophic respiration, total landscape (live and dead vegetation) carbon, standing-crop (live) carbon, and gross primary

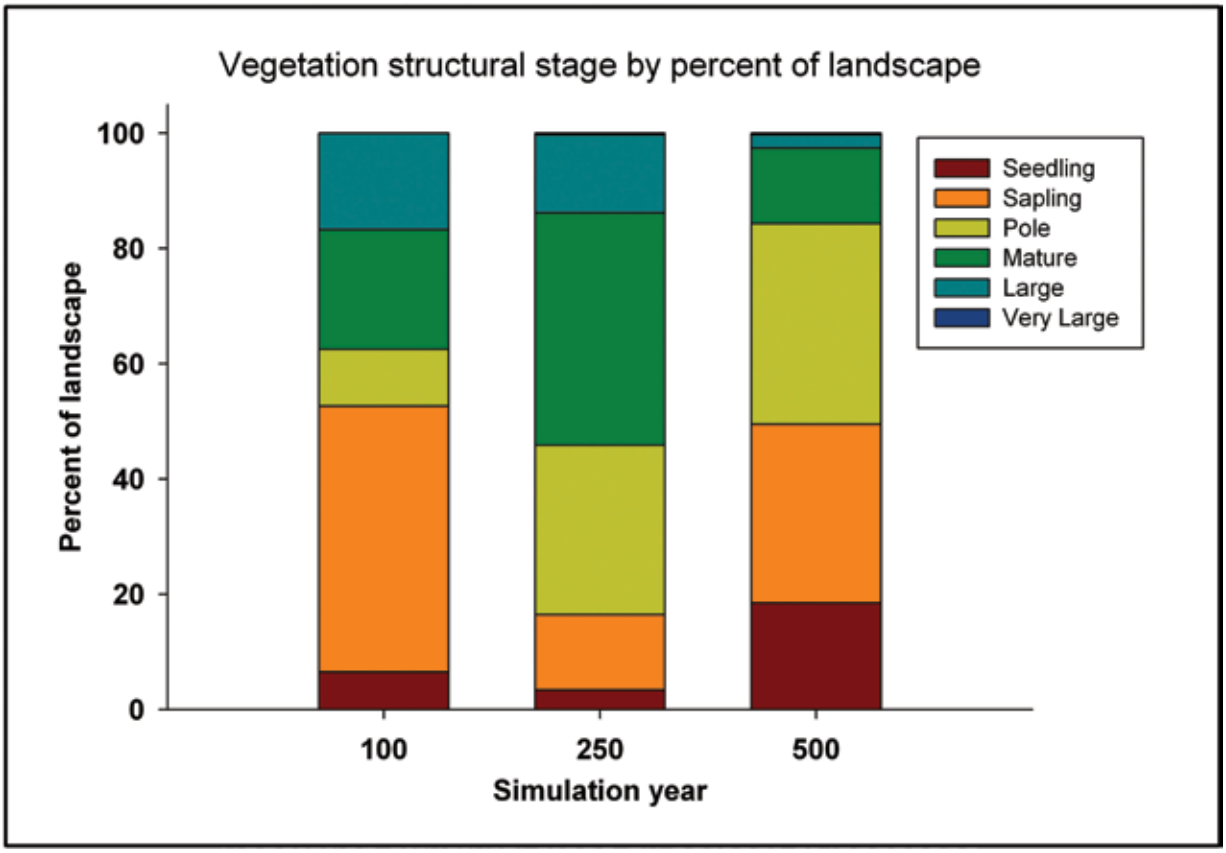

Figure 22. Structural stages (seedling, sapling, pole, mature, large, and very large) by percent of the simulation landscape at simulation years 100, 250, and 500.

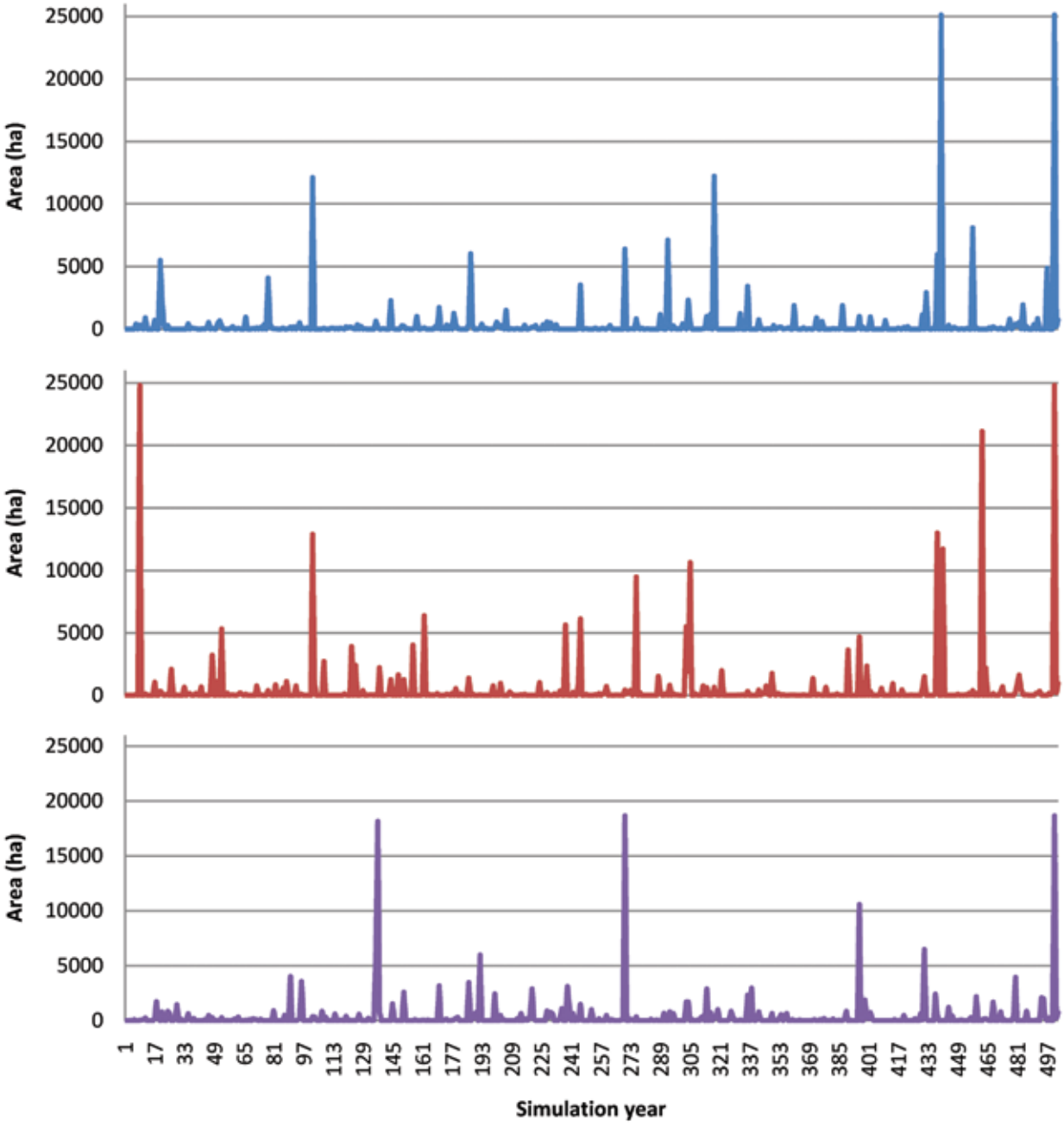

Figure 23. Total area burned during each simulation year for three model replicates, 500-year simulation, Lake McDonald watershed, Glacier National Park, USA.

productivity. These outputs are used to evaluate carbon dynamics across the simulation landscape—for example, to compare carbon emissions from wildfires (net loss of carbon from the landscape) to carbon stored on the landscape in the form of live and dead vegetation. High annual carbon emissions from fire, resulting from a large number of landscape acres burned and/or high-intensity fires, temporally co-occur with a decrease in landscape total carbon stores due to consumption of live and dead vegetation (Figure 24). The difference between total stored (sequestered) carbon and total carbon emissions from wildfires and autotrophic and heterotrophic respiration can be used to describe a dynamic landscape carbon budget across the simulation period.

The sample graphical and tabular outputs described and presented here describe a single model scenario that represents historical climate conditions with no suppression or fuels treatments implemented on the landscape. Previous and ongoing FireBGCv2 research projects have been implemented with factorial simulation designs that test the effects of management scenarios and/or potential future climate conditions on ecosystem patterns and processes; in this context, visualization and analysis of output should highlight key differences that result from variation among factors (Keane and others 1997, 1998, 1999).

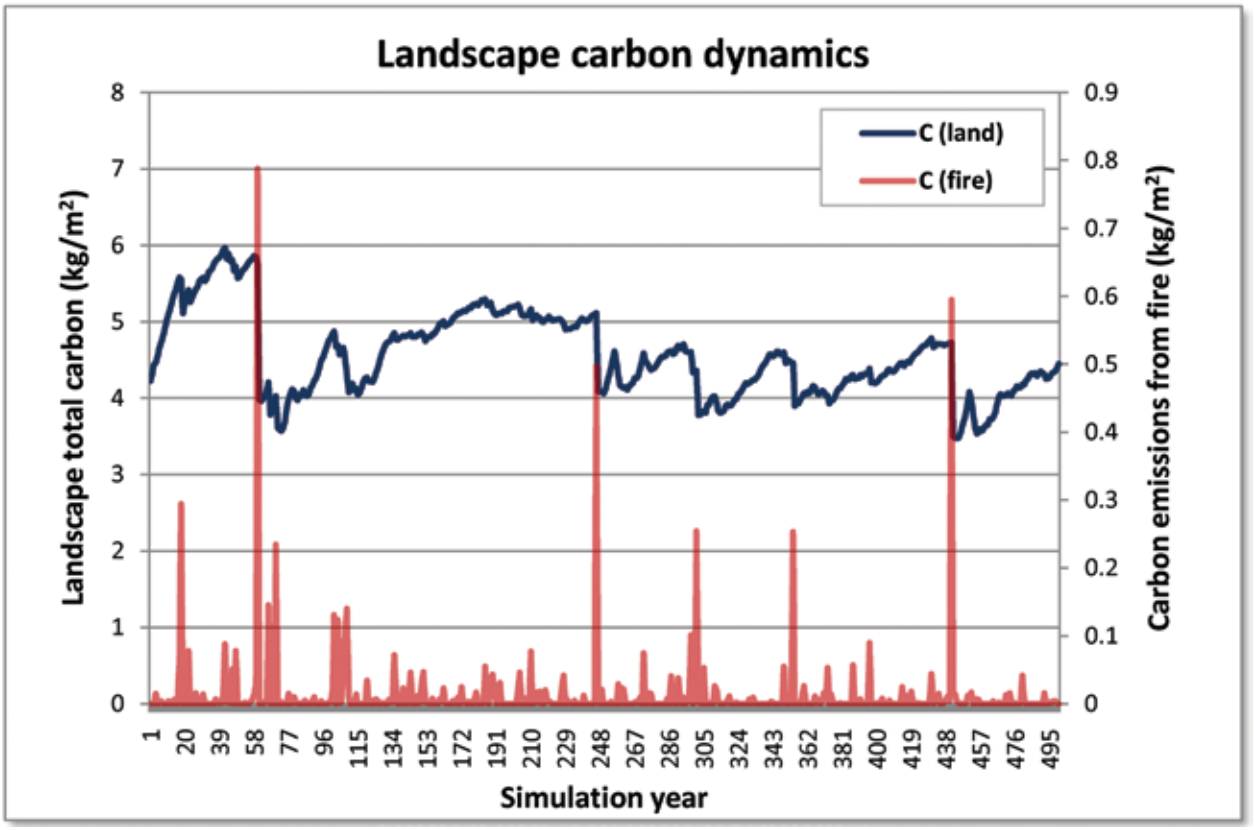

Figure 24. Carbon emissions from fire (kg m^{-2}) and landscape total carbon (kg m^{-2}) across the 500-year simulation period, McDonald watershed, Glacier National Park, USA.

Discussion

Model Limitations

The downside of using a highly mechanistic model to simulate landscape dynamics is that the resultant behavior can often be unstable, non-linear, and inexact. The response surfaces of any model, especially a mechanistic one, are bounded and dictated by their algorithms and the parameterization of those algorithms. Often, model parameters will be in conflict with each other. For example, the specified fire return interval could be at odds with the species parameters, which may result in odd behaviors and questionable predictions. It is critical that intermediate simulation results be compared with reality or field data under specially designed simulation parameterizations so that the model can be calibrated and adjusted to achieve sensible simulation results. However, the most difficult task of a modeler is to determine if a strange simulated time series is a viable, ecologically possible result or if it is simply wrong because of incompatible parameterizations and initializations. We suggest that users simulate historical landscape conditions using historical weather, fire frequency and fire size parameters, and species parameters and then create a suite of diagnostic output variables to evaluate whether the model is realistically simulating historical landscape dynamics (Figure 14). If not, then site and species parameters can be adjusted to nudge results closer to observed characteristics by comparing simulation results to historical study results. If actual conditions still cannot be approximated, then the model may need adjustment and the computer code may need to be modified.

One important limitation of FireBGCv2 is the absence of the close linkage between fire spread and fire behavior with fuels and weather. It was difficult to stop simulated fires from spreading into stands that tend to be moist for many parts of the year, such as spruce-fir forests. As a result, the model tends to overestimate the number of fires in mesic communities because fire is constantly spreading into those areas from surrounding, more flammable communities.

The relationship between the average fire size and fire size distribution parameters can cause some confusion and problems in parameterization and interpretation of model results. The average fire size (in Site.in) is the average size of the fires by site on the simulation landscape, and it is used to scale the point estimate of fire probability to the polygon level. The fire size distribution parameter is a constant in the fire size distribution equation that determines the ultimate size of a simulated fire. This parameter can be approximated from the average fire size, but in FireBGCv2 simulations, it often turns out to be roughly one-third of the average fire size to match observed fire regimes. We recommend that the average fire size be determined from available data, and then that the fire size distribution parameter be estimated using calibration techniques. The model should be executed, and fire statistics from the Fire Output file should be inspected to determine if the fire size distribution parameter should be altered to obtain more realistic fire regime simulations.

The two site-level fire parameters (average fire size and fire return interval) strongly influence fire and vegetation dynamics. A consistent methodology for setting these parameters to achieve appropriate simulated fire frequencies is important. As discussed, the historical data available for estimating these parameters are limited. Due to scale and model efficiency, fires smaller than 0.5 ha are not modeled. This removes a portion of the left end of the fire size distribution curve, which is where the largest numbers of fires occur, and increases the mean fire size. Even if there are excellent historical data to estimate the fire parameters (return

interval and average size), there will still be differences between simulated fire regimes and actual historical fire regimes. It is difficult to simulate fire regimes from two sets of independent fire parameters (fire occurrence probabilities and fire size distributions) and expect perfect agreement with historical conditions. Fire, like many natural processes, is highly complex, and any attempt to model it is a simplification of the actual dynamics. Fire operates at many different spatial and temporal scales, and its occurrence is influenced by many factors, such as vegetation, weather, wind, and topography, that also operate at different spatial and temporal scales. As a result, it is difficult to realistically simulate fire without building overly complex models that are difficult to parameterize and inefficient to run for large landscapes over long simulation periods. Integrating fine-scale processes of weather and fuel into the model using FARSITE routines would make the model computationally intensive and would dramatically reduce the efficiency of the model runs. Therefore, results of each FireBGCv2 simulation should be compared with expert experience and any available data to determine if output is reasonable because of the overly simplistic model algorithms. If not, then the parameters should be adjusted to more closely approximate reality.

Simulation Issues

Much of FireBGCv2 modeling is about balancing realistic simulations of fire and vegetation dynamics with the often opposing goal of computational and logistical efficiency. This struggle becomes more important as simulation landscapes increase in size, resolution, and complexity. We found that simulation times tended to increase exponentially with increasing landscape size and time spans, but conversely, the use of larger simulation landscapes were logistically simpler and produced better simulation results. There is an optimal landscape size at which the model becomes efficient and overall processing time is optimized. We found that 50,000- to 250,000-ha landscapes at 30-m pixel resolution work well, but this may change with topographic and succession pathway complexity and as computer technology improves. A spatial data layer pixel resolution of 30 m works well for many FireBGCv2 applications, but as landscapes get large (>100,000 ha), it is suggested that the pixel resolutions also increase proportionately. Using *LANDSUM*, we found little loss in simulation detail when we went from 30-m to 100-m resolution (Karau and Keane 2007).

The arbitrary delineation of a simulation landscape is somewhat problematic in that the landscape edges create artificial boundaries across which fire cannot burn. In real landscapes, water, rock, or topography may create boundaries that influence fire spread, but on most simulation landscapes, the simulation edge does not follow natural fuel break boundaries and may cut right through areas of constant vegetation or topography, through which fires would naturally spread. Another problem is that areas near the edges of a landscape have a limited number of surrounding pixels from which a fire can spread into the landscape. This problem is further exacerbated by wind and its prevailing direction because fire is spread by wind and slope vectors at variable directions and speeds for the entire simulation. All things being equal, this means that pixels near the direction where the wind is originating (south and west edges, for example) have the lowest probability of burning, while those nearest to the direction where the wind is blowing (the north and east, for example) have the highest probability of burning. The best way to mitigate the edge effects in a FireBGCv2 simulation is to surround the simulation landscape with a buffer. A buffer is created by making the simulation landscape larger and then stratifying the results into two regions—the buffer and the context area—that together comprise the simulation landscape. If the buffer area is large enough, the relative position of pixels within the landscape will not influence burning and fire frequency within the context area, and the fire frequency in the leeward buffer region of the context area should not be substantially different

from the fire frequency for any other part of the context area. Each landscape is unique, so buffers will be different for each setting.

It is important that there is a consistent methodology for testing the parameters established for the simulation landscape. FireBGCv2 has an extensive error-checking routine that scans the input data for inconsistencies between the various input files that could cause problems during simulation. However, there may be problems with the input data that the model does not recognize as inconsistencies but that still may cause unexpected results. And while the FireBGCv2 model has undergone an extensive de-bugging process, it is possible that some new, unique circumstance will arise that will cause unexpected results. We recommend a thorough quality control process for all parameters, initialization data, and simulation results. Ideally this could be done as a series of queries in a database environment that would check for consistencies between parameters and initial values. If there are any suspicious results, further analysis should be done to determine the reason for such results and whether they make sense ecologically.

It appears that a significant number of simulation years are required before the trends in response variables stabilize and the annual simulations achieve some level of equilibrium. This stabilization time may take one to three centuries on simple landscapes and more than 500 years on complex landscapes. We found that using the current landscape to initialize the historical landscape could be inefficient on two levels. First, the current landscape often contains too many polygons, and the simulation times increase as numerous polygons are added by the continual division of polygons by fire. Second, the current landscape is so departed from historical conditions that it takes an excessively long time for this landscape to reach equilibrium. However, in FireBGCv2, the use of current conditions for initialization is often the only possible option.

Potential Improvements

At the center of future simulation research is a need for comprehensive data to run and validate future models. The balance of data needs versus model advancement reflects an imperative for collaboration between field ecologists, who provide data and equations, and modelers, who must then integrate that knowledge to provide descriptions of phenomena at different spatial and temporal scales. It is critical that extensive field programs be intimately integrated with simulation efforts to ensure sufficient parameter and validation data are measured for model applications. Temporally deep, spatially explicit databases created from extensive field measurements are needed to quantify input parameters, describe initial conditions, and provide a reference for model testing and validation, especially as landscape fire models are ported across large geographic areas and to new ecosystems (Cary and others 2006). For example, Hessl and others (2004) compiled a number of ecophysiological parameters for use in mechanistic ecosystem models, which has increased parameter standardization and decreased the time modelers spend on parameterization. New sampling methods and techniques for collecting data are needed to ensure the right variables are being compared at the right scales. Field data that are useful in simulation modeling should be stored in standardized databases, such as FIREMON (Lutes and others 2006), and stored on websites so that they are easily accessible for complex modeling tasks. Last, new instruments are needed to quantify important simulation variables such as canopy bulk density, to initialize and parameterize fire behavior models (Keane and others 2005).

Model validation and verification are difficult tasks with landscape models that simulate vegetation and fire dynamics over millennia time spans (Keane and Finney 2003, Keane and others 2004b). There is a lack of spatially explicit, historical time series data that are in the right context to compare with model results. Validation data must have many characteristics to be useful for model validation.

First, the data must be described in the same format as model output; the mapped data must have the same categories as those simulated by FireBGCv2. Next, the historical data must be from many time periods. The comparison of one historical map with the simulation results provides only a qualitative or descriptive means of testing and verifying the model. Multiple maps would provide the basis for an objective statistical comparison. And, since FireBGCv2 does not replicate historical fire sequences because it is a stochastic model, it would be difficult to compare past fire patterns with corresponding simulated patterns. Last, the data must be incorporated into maps that describe historical conditions across the entire landscape. Because of these limitations, we could find no historical datasets to comprehensively validate FireBGCv2. This leaves validation of the algorithms and disturbance parameters as the only way to verify that the model is producing realistic results. Keane and others (2002a) compared simulated fire area and pattern statistics from a 1000-year LANDSUM run (FireBGCv2 uses some LANDSUM fire simulation routines) to the historical fire atlas created by Rollins and others (2001) and found excellent agreement between the distributions of fire size and patch shape.

Input File Structure

File Design

All input and output files in FireBGCv2 are in ASCII format, also referred to as text or flat file format (Figure 10). Each ASCII file is configured as a vertical or horizontal file, where vertical files contain only one input value per line with a descriptor of that input value following the number, and horizontal files contain more than one value per line and resemble tables. Most FireBGCv2 input files are vertical (provides greater understanding and error management) and all output files are horizontal (increases efficiency). The first line of each FireBGCv2 input file is called a title line and is used to describe the file and its origins. There are 256 characters that are available for this descriptive title, which may also be used to identify the file author, project affiliation, model version, creation/edit date, and other useful information.

There are two types of files in FireBGCv2: parameter files (scenario) that describe various aspects of the simulation and input files (description) that represent site, stand, and tree conditions. Scenario files are totally subjective, but description files must describe true ecological conditions and are usually developed from primary field data. FireBGCv2 files are also cycling or discrete. Cycling files contain the same format that is cycled downward or repeated for each similar instance. For example, species parameters are cycled vertically for each species in the simulation. Discrete files do not cycle and always contain a discrete number of fields.

Model parameter and input files are described next, including suggestions for file management and user-specified customizations for simulation development. In addition, parameters and input files are described in the order in which they should be modified by new users.

Driver.in File

This driver file is a vertical discrete scenario file that contains the names and pathnames of all input files required for FireBGCv2 execution. The order of these files is absolutely critical. The structure of the file is as follows:

Rec	Variable	Description
1	None	This line is reserved for the title line
2	Sim	Input simulation file containing general simulation parameters
3	Climate	Input climate file containing climate parameters
4	Map	Input file containing names of input and output ASCII maps
5	Species	Input file containing parameters for individual tree species
6	Wildlife	Input file containing habitat suitability parameters
7	Manage	Input file containing specifics of management activities
8	Plant	Input file containing parameters for plant models
9	Pial	Input file containing special parameters for whitebark pine
10	Fuel	Input file with fuel model parameters for effects and behavior
11	Site	Input file containing parameters for sites on landscape
12	Stand	Input file containing initial input values for stand components
13	Tree	Input file with initializing values for all trees in stands

14	Echo	Output file displaying a summary of all input variables
15	Error	Output file showing all errors in input files and values
16	Restart	Output file for *BGC* restart variable initial values
17	SeedDispersal	Output file for seed dispersal parameters
18	StandDay	Output file containing daily values for specified stand-level variables for each day
19	StandYear	Output file containing values for specified stand-level variables for each year
20	TreeYear	Output file containing values for specified tree-level variables for each year
21	TreeList	Output file containing a tree list for each stand for each year
22	StandFire	Output file showing all fire statistics for individual fires
23	Disturb	Output map prefix for storing fire and management maps
24	Manage	Output file for storing all management actions
25	LandYear	Output file reporting carbon and fire variables at landscape scale

All pathnames in this file should be valid filenames in that they start in column one and proceed left to right without blank spaces or commas. It is recommended that a space be skipped after the file name and then that a descriptive statement be included that describes the file content. There is space for only 256 characters on this record. For all output variables, the word NONE entered in place of a filename and pathname dictates that no output will be written for that file type.

Sim.in File

The simulation file is a vertical discrete scenario file that contains general simulation parameters related to the execution of the entire program. Some parameters in this file serve as error checks for parameters in other files, while other parameters are critical for FireBGCv2 simulation. The structure of the file is as follows:

Rec	Variable	Description
1	None	This line is reserved for the title line
2	verbose	Verbose flag (0-no messages, 1-partial, 2-full, 3-full for debugging)
3	span	Simulation time span in years
4	bgcinit	*BGC* process (0-initialize from bare ground and store, 1-initialize from stand data and store, 2-use stored values, 4-stand data, 5-no spinup)
5	nsites	Number of sites on the modeled landscape
6	nspecies	Number of species in the species parameter file
7	nwild	Number of wildlife species in the wildlife file
8	nmanage	Number of management activities in the management file
9	nplant	Number of undergrowth plant models in the plant input file
10	nfmod	Number of fuel models in the fuel model input file
11	nwyr	Number of weather years in the daily weather file for all sites
12	wxseq	Weather data cycle (0-in sequence, 1-random, 2-front to back)
13	smod	Succession model driver (0-*BGC*, 1-mechanistic gap, 2-simple gap)
14	seedint	Seed dispersal map update interval in years
15	outint	Output thematic map interval in years
16	seedrun	Seed dispersal option (0-new run, 1-old run, 2-new run store values)
17	runopt	Fire sim option (0-new run, 1-old run, 2-new run store ignitions)
18	firemod	Fire spread model (1-FARSITE, 2-LANDSUM, 3-Cell automata)
19	fireprob	Fire ignition probability calculation: (0-default, 1-weibull hazard, 2-weibull survivor, 3-fri)

```
20   firesupp       Level of fire suppression: number between 0 and 1 where 0 is
                    historical fire regime and 1 is total suppression
21   habsuit        Method for computing wildlife habitat suitability (0-no
                    calculation, 1-stand level, 2-tree level)
22   beetle         Starting year of beetle epidemic (YYYY)
23   rust           Starting year of rust infection epidemic (YYYY or -YYYY)
24   phenology      Phenology option (0-constant, 1-simulated from White model)
25   rnscheme       Random number scheme (0-fully random, 1-use same random numbers)
26   rngen          Random number generator (See tools.c for IDs)
27   parea          Area of simulation plot in square meters
28   hsize          Canopy height increment in meters
29   treemax        Maximum tree density (t/m2) use as multiplier (use -1 for no use)
30   print_int      Print interval for outputting stand and tree data (years)
31   bday           Beginning day for daily stand output (Julian date)
32   eday           Ending day for daily stand output (Julian date)
33   treeID         Tree ID number for yearly tree output
34   varindxnum     Variable index numbers for printing to daily stand output file
35   varindxnum     Variable index numbers for printing to annual stand output file
36   varindxnum     Variable index numbers for printing to tree yearly output file
-------------------------------------------------------------------------------
```

A few of these parameters warrant additional discussion. The verbose flag describes how many messages the user wishes displayed while the program is executing. The simulation time span (span) in years is the number of years that will be simulated by the model.

The variable **bgcinit** is a flag that represents how the *BGC* succession model driver within FireBGCv2 is initialized. A value of 0 initializes the *BGC* submodel in the current execution, while a value of 1 uses a previous initialization. The previous initialization is stored in the restart file identified in the Driver.in file.

The next set of parameters identify the number of entities in the simulation: **nsites** is the number of sites represented in the Site.in file; **nspecies** is the number of species in the Species.in file; **nwild** is the number of wildlife species in the Wildlife.in habitat input file; **nmanage** is the number of management activities defined in the Manage.in file; **nplant** is the number of plant models in the Plant.in file; and **nfmod** is the number of fuel models in the Fuel.in file.

The next two variables describe the weather data specified by site in the Site.in file. All weather files in the simulation (one per site) must have the same number of records (days) and same number of weather years (whole years with 365 days, no leap years), as identified with the variable **wxyr**. The flag **wxseq** identifies how this weather record will be used over the long simulation time: a value of 0 results in random selection of each year from the full weather record, a value of 1 results in the entire record being cycled for the entire simulation, and 2 indicates that the starting year of the cycle is randomly chosen.

The **smod** variable indicates the succession model to use for vegetation simulation. Options include a fully integrated *BGC* simulation (option 0), a mechanistic gap model with over 70 percent of the *BGC* structure built into a gap model without the overhead (option 1), and a simple gap model, in this case the *FIRESUM* model (option 2). For additional discussion of succession model drivers, refer to the "Stand Processes" section.

The next two variables identify the interval at which processes are simulated. The **seedint** variable represents the number of years between seed dispersal simulations. Because seed dispersal simulations are computationally intensive, this process should not be performed every year. The **outint** variable determines the output map (thematic) update intervals in years.

The **seedrun** flag indicates the seed dispersal model run option—as a new run without any storage of information for use subsequent runs (option 0), using

the previous run's initialization as a primer with no new initial dispersal run (option 1), or as a new run with storage of initial values for use in subsequent runs (option 2).

The **runopt** flag is used to describe how fires are simulated in FireBGCv2. If 0 is entered, the program will call the fire spread models (*FARSITE* or *LANDSUM*) each time a fire is simulated. This is the most computationally-intensive option; alternatively, if 1 is entered, fires are taken from a set of files that were stored from previous runs. Option 2 indicates that new fires are generated for the simulation run, but all simulated fires are stored for use in subsequent runs.

Three variables implement fire behavior options in the simulation. The **firemod** flag indicates the fire spread model that is used to model fire across the landscape. A 0 selects the *FARSITE* model, and a 1 selects the *LANDSUM* fire spread algorithms. For additional discussion of these fire spread models see "Wildland Fire" in the "Landscape Processes" section. No cell automata model has been implemented in the FireBGCv2 model yet but will be included in a later release as option 2. The **fireprob** variable is a fire ignition probability calculation in which 0 is the default value, 1 indicates a weibull hazard function, 2 selects a weibull survivor function, and 3 uses the fire return interval defined for each site on the simulation landscape. The **firesupp** variable specifies the level of fire suppression, entered as a number between zero and one where 0.0 is the historical or native fire regime and 1.0 is the full suppression of all fires.

The **habsuit** flag defines the method for habitat suitability calculations. The habitat suitability algorithm can key habitat suitability indices to stand-level characteristics (option 1) or tree-level characteristics (option 2). The tree-level calculation option computes habitat suitability indices for each tree in the stand.

The **beetle** and **rust** variable values are used to indicate the simulation year in which a beetle epidemic or rust epidemic starts, respectively. A value of 9999 is used to specify no rust or beetle epidemic in the simulation. For the **rust** variable, a negative value (for example, -9999) indicates that all five-needled pines included in the tree list (Tree.in) will be counted as live trees, even if they are entered as dead trees in the input file.

The **phenology** flag is used to specify either a static simulation of phenology using constants in the Species.in file (option 0), or dynamic simulation of phenology using algorithms from White and others (1997) (option 1). The FireBGCv2 model does not use the phenology flag unless *BGC* is selected as the succession model driver (**smod***)*.

The **rnscheme** and **rngen** flags are used to specify how stochastic algorithms will use random numbers in the model. The **rnscheme** has two modes: option 0 specifies that the random number sequence will be different across multiple FireBGCv2 executions and option 1 specifies that the random number sequence will be exactly the same across multiple executions. This is important if a sensitivity analysis requires that model stochasticity remain constant.

The variables **parea** and **hsize** are the only decimal values in the simulation input stream. The variable **parea** is the area of the simulation plot (m^2) that is used to represent the stand area. The variable **hsize** is the thickness (m) of the canopy layer, which is important for computing light dynamics under the canopy. It is recommended that **parea** be set to 400 m^2 and **hsize** be set to 1.0 m when the majority of trees in a plot are below 35 m in height. The **treemax** variable is a multiplier for maximum tree density that is used to govern the number of trees in a simulation.

The next set of parameters defines how intermediate output will be printed from FireBGCv2. The variable **print_int** indicates the printing interval in years for tabular output—for example, if 10 is entered, output will be printed every 10 years. The variables **bday** and **eday** specify the beginning and ending Julian dates to print daily calculations (for example, 1 and 365 for an entire simulation year). **TreeID** indicates the tree ID number for which to print daily calculations between **bday** and **eday** in Tree.Year output file. For example, a value of 1 for TreeID will

print species, DBH, height, and height to base of crown for the first tree in every stand throughout the simulation period.

The final three variables in the Sim.in file are sets of numbers that specify the output variables printed to the stand.day (daily stand-level intermediate variables), stand.year (annual stand-level intermediate variables), and tree.year (annual tree-level intermediate variables) output files. There are a maximum of 40 variables that can be printed out for each set. See Table 7 for a list of available variables and ID numbers.

Climate.in File

The climate file contains parameters that alter daily input weather streams to create a climate change scenario, including offsets of atmospheric CO_2, temperature, precipitation, and nitrogen deposition and fixation rates. The climate file consists of both universal and seasonal parameters, in which universal parameters define a ramping period for climate changes and a consistent CO_2 and nitrogen environment, and seasonal parameters allow for intra-annual offsets in temperature, precipitation, vapor pressure deficit, and solar radiation. The structure of the file is as follows:

Rec	Variable	Description
1	None	This line is reserved for the title line
2	year_start	Starting year of climate change scenario
3	year_end	Ending year of climate change scenario
4	seas	Number of seasons in this climate change scenario
5	co2_start	Starting atmospheric CO2 concentration (ppm)
6	co2_end	Ending atmospheric CO2 concentration (ppm)
7	nd_start	Starting nitrogen deposition rate (kg N m^{-2} $year^{-1}$)
8	nd_end	Ending nitrogen deposition rate (kg N m^{-2} $year^{-1}$)
9	nf_start	Starting nitrogen fixation rate (kg N m^{-2} $year^{-1}$)
10	nf_end	Ending nitrogen fixation rate (kg N m^{-2} $year^{-1}$)
11	filename	Filename of these parameters by year of simulation
12	None	Filler line noting each weather scheme is repeated for each season
13	seas1	Title for season 1, ex: Winter season (jan-feb)
14	jdate	Julian Date of last day in this season
15	tmax	Final Tmax offset (degC) by end of climate change scenario
16	tmin	Final Tmin offset (degC) by end of climate change scenario
17	ppt	Multiplier for precipitation (dimensionless)
18	vpd	Multiplier for VPD (vapor pressure deficit) (dimensionless)
19	srad	Multiplier for radiation (dimensionless)
Repeat lines 13-19 to define another season (ex: season 2, Spring (mar-may)		

The universal parameters **year_start** and **year_end** define the simulation period over which the climate offsets entered in the Climate.in file will be applied; for example, **year_start** and **year_end** values of 1 and 100, respectively, indicate that the offsets defined for each season will be ramped incrementally across the first 100 years of the simulation. The next set of parameters defines starting and ending values for three important climate and land use change variables: (1) the carbon dioxide concentration (ppm), (2) nitrogen deposition rate (kgN m^{-2} yr^{-1}), and (3) nitrogen fixation rate (kgN m^{-2} yr^{-1}), specified by **co2_start**, **co2_end**, **nd_start**, **nd_end**, **nf_start**, and **nf_end**, respectively. The final universal parameter in the Climate.in file identifies a secondary file that can be used to specify climate change parameters by simulation year. If the **filename** parameter is entered as "NONE," FireBGCv2 uses the parameters in the previous nine file lines

to simulate a climate change scenario; however, if a **filename** is entered, a file must be created that lists the nine previous parameters by year. This option is used if a ramping strategy is not warranted or sufficient.

The seasonal portion of the climate file may consist of up to six user-defined seasons, where each season is defined by a last Julian date and a number of abiotic climate-related variables. Variables **tmax** and **tmin** are final maximum and minimum temperature (°C) offsets used during the climate change scenario. For example, the maximum temperature for any given day will be T + **tmax** at the end of the climate change scenario. The variables **ppt**, **vpd**, and **srad** are multipliers (values from 0.0 to 10.0) that define the maximum precipitation, vapor pressure deficit, and solar radiation, respectively, at the end of the climate change scenario. For example, a **ppt** value of 1.2 is equal to a 20 percent increase in precipitation at the end of the climate change scenario.

Map.in File

This critical file contains all the descriptors and filenames for all thematic layers (maps) used in model execution and output from FireBGCv2 simulations. This is a vertical discrete scenario file with the following structure:

Rec	Variable	Description
1	None	This line is reserved to describe the file
2	polymeth	Method of polygon creation
3	cellsize	The size of a square pixel in meters
4	rows	Number pixels in a row of the map
5	cols	Number pixels in a column of the map
6	xllcorner	UTM North coordinate of the lower left pixel
7	yllcorner	UTM East coordinate of the lower left pixel
8	nodata	Value for missing data (-1)
9	minmapunit	Minimum map unit for output (ha)
10	demname	DEM filename or pathname: Elevation grid map filename
11	initstandname	Initial polygon filename
12	zone	Zone filename for simulation area, context landscape, buffer
13	outmapname	Dynamic thematic map filename
14	firemap	Fire intensity maps for each fire year
15	xul,yul	x,y coor upper right submap
16	xlr,ylr	x,y coor lower left submap
17	None	This line is reserved to describe the next two fields
18	None	This line is reserved to describe the next two fields with headers
19	mapper[]	Array storing the requested FireBGCv2 output maps
20	None	This line is reserved to describe the next two fields
21	None	This line is reserved to describe the next two fields with headers
22	wildlife[]	Array storing the requested wildlife habitat suitability maps

The **polymeth** flag describes the method of polygon creation, in which a value of 0 indicates that new stands can be created along the boundaries of a fire and an entry of 1 means that the entire stand will burn if a fire enters that stand. The **cellsize** should correspond to the pixel size (m) in the maps' ASCIIGRID file headers. The variables **rows** and **cols**, and the coordinates **xllcorner** and **yllcorner**, are taken directly from the ASCIIGRID headers and specify the number of rows and columns in the map and the UTM coordinates of the lower left corner of the map. These variables serve as an error check for map input. The **nodata** variable is the value of a pixel given if there is no data for that cell, such as any pixel outside the simulation area. The **demname** is the name of the digital elevation model (DEM)

used to define the simulation area. This map is important because any value in this map that is not equal to **nodata** is considered inside the simulation area. The **initialstandname** file is a raster file for which each pixel is assigned a stand number. Stand numbers should be ordered to reflect their location within sites. The zone filename is an ASCIIGRID map in which cell values of 0 define a buffer around the core simulation landscape (see the "Map Creation" section for more information), and cell values of 1 or higher define the context landscape for which results will be printed. The **outmapname** sets the prefix and pathname for thematic maps defined with the **mapper** and **wildlife** arrays (described below).

If thematic output is only needed for a small portion of the entire simulation landscape the upper and lower left and right coordinates (**xul**, **yul**, **xlr**, and **ylr**) (in pixel coordinates, not map coordinates) can be entered. Enter -999 for these four values if no subarea is desired. The next two lines are used to describe the thematic and wildlife habitat maps that are to be printed at the time interval specified in the Sim.in file. The arrays **mapper** and **wildlife** are used to store toggle switch values (1 for each map that is to be printed, and 0 if the map is not desired) for variables whose order corresponds to thematic output variables or wildlife species, respectively. There is space for twenty values per line. The wildlife maps reference the wildlife ID numbers in the Wildlife.in file, and thematic maps are listed in the following order:

Index	Description	Variable
1	Polygon ID number for this stand	polyID
2	Fire Atlas with number cumulative fires	numfires
3	Dominant species ID (Canopy Cover)	sppID
4	Dominant species ID (Basal Area)	sppID
5	Dominant species ID (DBH)	sppID
6	Dominant species ID (leaf area)	sppID
7	Dominant species ID (biomass)	sppID
8	Structural stage of stand	code
9	Age of stand based on years since dist	years
10	Age of oldest individual on stand	years
11	Stand basal area	m^2 ha^{-1}
12	Stand canopy cover	percent
13	Stand leaf area index	m^2 m^{-2}
14	Gross primary productivity	kgC m^{-2} $year^{-1}$
15	Net primary productivity	kgC m^{-2} $year^{-1}$
16	Net ecosystem production	kgC m^{-2} $year^{-1}$
17	Evapotranspiration	kgH_2O m^{-2} $year^{-1}$
18	Maintenance respiration	kgC m^{-2} $year^{-1}$
19	Aboveground carbon	kgC m^{-2}
20	Total carbon	kgC m^{-2}

Input Map Creation

More needs to be said about the creation of the FireBGCv2 input maps. FireBGCv2 reads thematic layers into the model in ASCIIGRID format, with a file structure that contains header information, data values, and "no data" values. These ASCIIGRID layers are created from raster maps (gridded pixels) that are usually processed in a GIS software package such as ESRI ArcMap. To create the required set of input maps, a user first selects a simulation area, ideally near 1000 by 1000 pixels in size. All attempts should be made to minimize the number of "no data" pixels within the map. Watershed boundaries make acceptable simulation landscape boundaries, but the odd shapes of watersheds almost always result in an abundance of "no data" pixels outside of the watershed boundary because ASCIIGRID input maps are always represented as a square array of pixels. Users

should add a spatial buffer around the core simulation landscape to ensure that fires are allowed to spread into the simulation landscape without artificial edge effects resulting from the restricted simulation boundary.

Three map layers (ASCIIGRID files) are required for FireBGCv2 execution. The first input map is a DEM. The DEM data can be acquired from the USGS National Elevation Dataset (http://ned.usgs.gov/). Users should order an area much larger than the proposed simulation area (at least five times the size) and then clip out an area that corresponds to the project simulation landscape plus an additional buffered area around the core landscape.

The second input map is the initial stand (polygon) map. This map spatially represents all simulation stands on the landscape. The stand map is created from satellite imagery, digitized photo-interpreted stand delineations, or some other existing vegetation mapping product. We recommend that stands be at least 5 ha to avoid bogging down simulations with an excessive number of stands. Also, stands should not exceed 250 ha in order to avoid oversimplification. Each stand must be assigned a unique stand ID number.

The third required input map layer is a zone map. This map is a grid array with cell values of 0 that define the buffer area around the context simulation landscape and cell values of 1 or higher that delineate the context or core landscape. The zone map restricts output data printed in tables and thematic layers to just the core simulation landscape by trimming the buffer area.

The three required input map layers must share a common map area and pixel size, as defined in the ASCIIGRID header information, and must be present in the appropriate location, as defined in the Map.in file, in ASCIIGRID format.

Species.in File

The most important file in the FireBGCv2 simulation is the Species.in file. It contains all the parameters for the individual plant species modeled in FireBGCv2. Most of these parameters are described in detail in the Keane and others (1996) *FIRE-BGC* document. Species.in is a cycling vertical scenario file where the first line contains an ID or title information and the second line lists the number of species contained in the file. The third line is a species ID line that is not used in the model. The name variable is entered on the fourth line. A description of each variable is usually written after the numeric or alphanumeric input value—but at least one space must be skipped between the value and the description. Once all parameters for a single species are entered (see Table 8), the following line is the ID line for the next species, followed by a repeating set of parameters for that species. This structure continues for the entire tree species defined for a simulation landscape plus entries for grass and shrub functional types. The following describes the species parameters:

Var	Description	Units
name	Species 4-character name (2-genus, 2-species)	alphanumeric
sppID	Species ID number from master table	code
lifeform	Species lifeform index 0-trees, 1-shrubs, 2-herb	code
vegtype	Vegetation type: 0-evergreen, 1-deciduous	code
	Ecophysiological parameters	
ic	Canopy interception coefficient	m LAI^{-1} day^{-1}
k	Canopy light extinction coefficient	dimensionless
all_to_proj	All-sided to projected leaf area ratio	m2 m^{-2}
saplai	SapwoodC to leaf area ratio	kgCsap m^{-2}leaf
sla	Specific leaf area of a projected area basis	m2 kg C^{-1}
shade_sunSLA	Ratio shade to sunlit SLA	dimensionless

leafNrub	Fraction of leaf N in Rubisco	dimensionless
gl_smax	Maximum canopy conductance (gmax)	m sec^{-1}
gl_c	Leaf cuticular conductance (gc)	m sec^{-1}
gl_bl	Leaf boundary layer conductance (gb)	m sec^{-1}
psi_open	Leaf water potential at field capacity	-MPa
psi_close	Leaf water potential at stomatal closure	-MPa
vpd_open	Min Vapor pressure deficit to affect conduct	Pa
vpd_close	Max Vapor pressure deficit to affect conduct	Pa
	Carbon to nitrogen ratios	
leafCN	C:N ratio for live leaves	ratio
litterCN	Critical litter C:N ratio	ratio
frootCN	Critical fine root C:N ratio	ratio
lstemCN	Live wood C:N ratio	ratio
dwoodCN	Dead wood C:N ratio	ratio
duffCN	Critical duff C:N ratio	ratio
	Annual turnover fractions	
leaffr_turn	Leaf and fine root turnover fraction	kgC kgC^{-1} $year^{-1}$
lstem_turn	Live wood turnover fraction	kgC kgC^{-1}
stem_turn	Stem, branch, and coarse root turnover frac	kgC kgC^{-1}
	Allocation parameters	
alloc_frootC_leafC	New fine root C to new leaf C	proportion
alloc_stemC_leafC	New stem C to new leaf C	proportion
alloc_lstemC_twoodC	New live wood C to new total wood C	proportion
alloc_crootC_stemC	New coarse root C to new stem wood C	proportion
alloc_growthC_storC	Current growth to storage C	proportion
alloc_leafC	Proportion to individual tree leaf C	proportion
	Decomposition parameters	
leaf_lab	Leaf labile carbon fraction	kg lab C kgC^{-1}
leaf_cell	Leaf cellulose carbon fraction	kg cell C kgC^{-1}
leaf_fscell	Leaf shielded cellulose fraction	kg ligninC kgC^{-1}
leaf_fucell	Leaf unshielded cellulose fraction	kg ligninC kgC^{-1}
leaf_lig	Leaf lignin fraction	kg ligninC kgC^{-1}
froot_lab	Fine root labile carbon fraction	kg lab C kgC^{-1}
froot_cell	Fine root cellulose carbon fraction	kg cell C kgC^{-1}
froot_fscell	Fine root shielded cellulose fraction	kg ligninC kgC^{-1}
froot_fucell	Fine root unshielded cellulose fraction	kg ligninC kgC^{-1}
froot_lig	Fine root lignin fraction	kg ligninC kgC^{-1}
dwood_cell	Wood cellulose carbon fraction	kg cell C kgC^{-1}
dwood_lig	Wood lignin fraction	kg ligninC kgC^{-1}
dwood_fscell	Downed wood shielded cellulose fraction	kg ligninC kgC^{-1}
dwood_fucell	Downed wood unshielded cellulose fraction	kg ligninC kgC^{-1}
	Gap model parameters	
r_shade	shade tolerance 1-5, 1-low to 5-highly tolerant	code
age_max	Maximum attainable age	years
ht_max	Maximum attainable height	m
dbh_max	Maximum attainable diameter	cm
ddmin	Minimum number degree-days for the species	degree-day
ddopt	Optimum number degree-days for the species	degree-day
wso	Minimum AET:PET ratio for the species	ratio
si50	Site index at 50 years	m

pcone	Probability of good cone crop	probability
nocrop	Years after cone crop when there is no crop	years
age_cone	Reproductive age	years
dinc_min	Minimum diameter growth increment	cm
duff_sura	Survival by duff depth - alpha coefficient	probability
duff_surb	Survival by duff depth - beta coefficient	probability cm^{-1}
btc	Bark thickness coefficient	cm bark cm DBH^{-1}
crat_init	Initial live crown ratio for mature trees	m m^{-1}
age_est	Tree establishment age	years
crat_est	Tree establishment live crown ratio	m m^{-1}
ht_est	Tree establishment height	m
	Phenological parameters	
leaf_out	Leaves start date	yearday
leaf_shed	Leave drop date	yearday
leaf_period	Time for leaf drop or growth	days
frost_late	Latest tolerable spring frost	yearday
frost_early	Earliest tolerable autumn frost	yearday
	Snag parameters	
snag_long	Average snag life	years

Species names and IDs must correspond for each FireBGCv2 run. The following are the species, species IDs, and four-letter acronyms for the Glacier National Park simulation design, as described in the "Demonstration" section:

Master species file

SppID	Common name	Four-letter acronym
1	Ponderosa pine	PIPO
2	Grand fir	ABGR
3	Douglas-fir	PSME
4	Lodgepole pine	PICO
5	Western larch	LAOC
6	Subalpine fir	ABLA
7	Engelmann spruce	PIEN
8	Whitebark pine	PIAL
9	Alpine larch	LALY
10	Western white pine	PIMO
11	Western red cedar	THPL
12	Western hemlock	TSHE
13	Quaking aspen	POTR
14	Grass	GRSS
15	Shrub	SHRB

It is important to note that the four-letter acronym used to name the species is the same acronym used in the Tree.in file.

Wildlife.in File

The Wildlife.in file is a cycling vertical scenario file with horizontal properties. It contains habitat suitability index values (scaled, often from 0 to 100) for wildlife species by cover type and structural stage. This file is a double-cycling file where the first or primary cycle is wildlife species and the secondary cycle is cover type. Any wildlife species or group of species can be implemented in this file, and there

is a limit of 20 wildlife species per FireBGCv2 run. A list of cover types is defined for each wildlife species. A cover type is nothing more than a dominance species classification with the species specified in the Species.in file as the list of possible cover types. Cover types that are not important habitat for a wildlife species need not be represented in the wildlife cover type list. Habitat suitability indices are then assigned to five structural stages for each cover type and wildlife species. A habitat suitability index can represent anything about a wildlife species. For example, it may represent the importance of cover type-structural stage combinations for the nesting of a particular woodpecker species or the relative abundance of forage for grizzly bears by each defined cover type-structural stage combination. The indices are assigned to each structural stage horizontally in the file (that is, there are five habitat suitability indices for each cover type line in the Wildlife.in file). The format of the Wildlife.in file is as follows:

Var	Record	Description	Units
name	1	Wildlife species name	alphanumeric
label	2	Wildlife species label (2-genus, 2-species)	alphanumeric
wildID	3	Wildlife species ID number	code
code	4	Number of included plant species	number
name	1	Four-letter acronym of plant species	code
sppID	2	Plant species ID number referencing SPECIES file	number
seedling	3	Wildlife habitat suitability index for seedlings	index
sapling	4	Wildlife habitat suitability index for saplings	index
pole	5	Wildlife habitat suitability index for poles	index
mature	6	Wildlife habitat suitability index for mature	index
oldgrowth	7	Wildlife habitat suitability index for oldgrowth	index

The variable **name** is a moniker for this wildlife species (for example, GrizzlyBear, Ungulates). The user has up to 64 characters to specify a name, but be sure there is no space if the name is more than one word. The **label** is a unique wildlife species acronym used in FireBGCv2 output, conventionally labeled as the first two letters of the genus and first two letters of the species. The **wildID** variable is a unique, sequential identification number that is used in model computations.

The cover type cycle now starts where habitat suitability values are specified in one record in the Wildlife.in file. The **name** is a four-character acronym for the cover type (plant species ID number). The user can put any label, but the **sppID** must correspond to a species ID number in the Species.in file. A habitat suitability value (number between 0 and 100, for example) must be entered for each of the five structural stages (**seedling**, **sapling**, **pole**, **mature**, and **oldgrowth**). The structural stages are defined by diameter classes as:

Seedling:	Less than 1.37 m tall
Sapling:	0 to 10 cm DBH
Pole:	10 to 25 cm DBH
Mature:	25 to 50 cm DBH
Oldgrowth:	Greater than 50 cm DBH

This file structure is repeated for multiple wildlife species.

Manage.in File

The Manage.in file is a cycling vertical scenario file that contains generalized parameters that define various management activities. This file is built as a list of management activities (called treatments) that are user-defined from three classes of anthropogenic disturbances. The first disturbance class is a clearcut that may

be specified with or without a subsequent broadcast burn. The second is a partial cut that can also be specified with or without prescribed fire. The partial cut can be tailored to mimic a thinning, selection cut, or any other silvicultural treatment. The third anthropogenic disturbance class is a prescribed burn that can be implemented at a wide variety of intensities. The user can specify any number or combination of these activity types to create a unique treatment by modifying the parameters that describe each activity type. This file is different from any other FireBGCv2 input file in that the variables that represent the parameters in a treatment are different across management classes. The format of the Manage.in file is as follows:

Rec	Variable	Description	Units
1	None	This line is reserved to describe the file	none
	THESE VARIABLES ARE CYCLED FOR EACH MANAGEMENT TREATMENT		
2	name	Unique Management ID name	alphanumeric
3	manage_type	Management type ID number (1-cc, 2-pc, 3-pb)	Code
4	alimit	First limitation parameter	variable
5	blimit	Second limitation parameter	variable
6	climit	Third limitation parameter	variable
7	dlimit	Fourth limitation parameter	variable
8	parm1	First design parameter	variable
9	parm2	Second design parameter	variable
10	parm3	Third design parameter	variable
11	parm4	Fourth design parameter	variable
12	spp1[MXSPP]	First species design parameter	spp code
13	spp2[MXSPP]	Second species design parameter	spp code
	NEXT MANAGEMENT TREATMENT		

The parameters that comprise management types (limit and parm roots) can be changed to create different management treatments. For example, there may be two clearcut treatments where clearcut (option 1) is specified as the management type, but there is a different list of retention species for each treatment. FireBGCv2 can handle any number of treatments, but each treatment must be defined as one of the three management types previously described. The definitions of each management type follow:

Clearcut harvest management type (code 1)

name	Name of this first management activity- no spaces; use only a single word
manage_type	Management treatment type ID number: (1-clearcut, 2-partial-cut, 3-prescribed burn)
alimit	Landscape annual clearcut maximum in hectares; the most area that can be harvested in one year
blimit	Maximum size of a clearcut in hectares
climit	Minimum basal area to be considered for harvest; all stands above this will be clearcut
dlimit	Not used in this management type
parm1	Residual minimum tree DBH in cm
parm2	Smallest merchantable tree DBH in cm
parm3	Fraction of slash left on the stand
parm4	Broadcast burn intensity kW m^{-1}; enter 0.0 if no burn is desired
spp1[MXSPP]	Retention species; (0-no, 1-yes, order corresponds to speciesID in SPECIES file
spp2[MXSPP]	Placeholder--This field is not used for clearcut management type

Partial-cut harvest management type (code 2)

name	Name of this first management activity- no spaces; use only a single word
manage_type	Management treatment ID number: (1-clearcut, 2-partial-cut, 3-prescribed burn)
alimit	Landscape annual partial-cut maximum in hectares; the most area that can be harvested in one year
blimit	Maximum size of a partial-cut area in hectares
climit	Minimum basal area between min and max DBH classes specified below to harvest
dlimit	Smallest merchantable tree DBH in cm
parm1	Minimum DBH to cut in cm
parm2	Maximum DBH to cut in cm
parm3	Fraction of slash left on the stand
parm4	Prescribed burn intensity kW/m; enter 0.0 if no burn is desired
spp1[MXSPP]	Residual species: 0-no, 1-yes, order corresponds to species ID in SPECIES file
spp2[MXSPP]	Placeholder--Not used for this management type

Prescribed burn management type (code 3)

name	Name of this first management activity– no spaces; use only a single word
manage_type	Management treatment ID number: (1-clearcut, 2-partial-cut, 3-prescribed burn)
alimit	Landscape annual burned with planned burns in hectares; the most that can be harvested in one year
blimit	Maximum size of the prescribed burn in hectares
climit	Minimum stand age for treatment
dlimit	Factor when multiplied by fire frequency is minimum age of treatment since last fire
parm1	Minimum fire intensity in KW m^{-1}
parm2	Maximum fire intensity in KW m^{-1}
parm3	Placeholder--Not used for this management type
parm4	Placeholder--Not used for this management type
spp1[MXSPP]	Residual species: 0-no, 1-yes, order corresponds to species ID in SPECIES file
spp2[MXSPP]	Placeholder--Not used for this management type

Plant.in File

This file contains the parameters for the plant model and guilds assigned at the site level. This is a cycling vertical scenario file that is used in the simulation of the undergrowth or non-forest species. This is actually a double-cycling file in that the file cycles for all plant models, and then through all guilds included in that plant model. The following is the generalized format for the Plant.in file:

Rec	Variable	Description
1	None	This line is reserved to describe the file
2	pnum	Number plant models in simulation--Models are assigned to site
3	None	This line describes the plant model
4	name	Name of plant model
5	plantID	Identification number of plant model
6	nguilds	Number of guilds (species) for this plant model
7	None	This line describes the guilds in the model
8	name	Guild name

9	id	Guild ID number
10	sppID	Species ID number--Reference species file
11	ht	Guild height (m)
12	bio_alpha	Biomass growth rate alpha (year^{-1})
13	bio_max	Maximum biomass(kg m^{-2})
14	pleaf	Proportion biomass leaf
15	pdead	Proportion dead at fire
16	pfuel	Dead fuel index (1-duff, 2-litter, 3-1hr, 4-10hr, 5-100hr, 6-1000hr, 7-shrub, 8-herb)
.	.	.
.	.	.
.	.	. Continue fields 8 to 16 until all guilds in model entered
.	.	. Start fields 2 to 7 for next plant model
.	.	. Continue fields 8 to 16 until all guilds in model entered

The plant model variables are defined as follows: **pnum** is the number of plant models in this file and is the only line that is not repeated or cycled in this file. The first cycle for each plant models then starts. The variable **name** is a moniker for this particular plant model. The user has up to 64 characters (for example, EricaceousShrubs) to specify a name, but be sure there is no space if the name is more than one word. The **plantID** is a unique plant model identification number that is used throughout FireBGCv2. The variable **nguilds** specifies the number of guilds present in each plant model.

The second cycle within plant models is then initiated and it is repeated for each guild in the plant model. Again, **name** is a useful label for this guild and this label shouldn't exceed 64 characters or contain spaces. The **guildID** is a unique number that identifies a guild across all plant models. The **guildID** field can be used to build several shrub and herb models stratified by productivity gradients. Species ID (**sppID**) is the ID number of a species represented in the Species. in file that best describes this guild. Guild height (**ht**) is the maximum height of each guild, which is derived from field data or other sources in the literature. Biomass growth is described by two exponential curve parameters: **bio_alpha** is the growth rate (kgB m^{-2} year^{-1}) and **bio_max** is the maximum biomass for this guild kgB m^{-2}). The proportion of total guild biomass that is leaf biomass is represented by **pleaf** and the proportion of total biomass that is dead after a fire event is **pdead**. The proportion **pdead** is assigned a fuel index **pfuel** that best describes the fuel component of this dead material (woody, shrub, or grass, for example). Cycle through these parameters until all guilds are represented for each plant model, then cycle through each plant model.

Pial.in File

This file contains the parameters for modeling whitebark pine regeneration on a landscape. This routine was originally included in the first version of *FIRESUM* and has been modified to be included in FireBGCv2. This is a static, descriptive file with the following fields:

Record	Variable	Description	Units
1	cmax	Maximum number of whitebark pine cones on a tree	cones
2	amin	Minimum cone producing age	years
3	dbhmin	Minimum diameter for cones to be produced	cm
4	birds	Number of birds on landscape that are caching seed	birds
5	spc	Number of whitebark pine seeds per cone	seeds cone^{-1}
6	spcache	Average number of seeds a nutcracker caches	seeds cache^{-1}

7	pfind	Proportion cached seeds recovered by the nutcracker	proportion
8	cyr[0]	Cone crop probability for a non-cone crop year	probability
9	cyr[1]	Cone crop probability for a poor cone crop year	probability
10	cyr[2]	Cone crop probability for a moderate cone crop year	probability
11	cyr[3]	Cone crop probability for a good cone crop year	probability
12	fmax	Maximum amount of canopy leaf area for caching	m2 m^{-2}
13	cpt	Maximum number of cones per tree	cones $tree^{-1}$
14	seeds_eat	Consumed seeds proportion	proportion

These values will probably not change by landscape or simulation area, so it is best to keep the values of all variables in this file.

Fuel.in File

This file contains the parameters for the fire behavior and fire effects simulation. This is a uniquely structured, descriptive file that vertically cycles by fuel model (with the number of fuel models specified in the Sim.in file), with each line representing an important parameter in the fire behavior or fire effects models. However, each line has eight values for each parameter for each fuel component (litter; duff; 1, 10, 100, and 1000 hr fuels; shrubs; and herbs). In addition, there are two sets of five parameters in each fuel model representing different sets of values for live and dead fuels. Therefore, this file can be described as a double-cycling vertical file (fuel type, live or dead, and fuel model) that is horizontally arranged. The final unique characteristic of this file is that there are three additional parameters that have only two horizontal values, where each value is a general representation of live and dead fuels; and three more single-value parameters that describe general characteristics of this fuel model. This file should probably never be modified once created, and the structure of this file is so singular that there is an example at the end of this section. The format of the Fuel.in file follows:

Record	Variable	Description	Units
1	None	Empty line used to describe file contents	none
2	None	This has headings for the live and dead	none
3	fuelID	Fuel model identification number	none
4	rhop_dead[MXDEAD]	Particle density	kg m^{-3}
5	lhv_dead[MXDEAD]	Heat content of fuel	btu
6	mps_dead[MXDEAD]	Surface area:volume ratio	cm^{-1}
7	moist_dead[MXDEAD]	Fuel moisture	percent
8	consume_dead[MXDEAD]	Percent fuel consumption	percent
9	rhop_live[MXLIVE]	Particle density	kg m^{-3}
10	lhv_live[MXLIVE]	Heat content of fuel	btu
11	mps_live[MXLIVE]	Surface area:volume ratio	cm^{-1}
12	moist_live[MXLIVE]	Moisture content	percent
13	consume_live[MXLIVE]	Percent fuel consumption	percent
14	mext[2]	Moisture of extinction	percent
15	fuel_bulk[2]	Bulk density of live and dead fuel	kg m^{-3}
16	om_bulk[2]	Bulk density of litter and duff	kg m^{-3}
17	fuel_depth	Depth of fuel bed	m
18	scm	Spread component when ignited	dim
19	wndfc	Wind reduction factor	dim

These fields are repeated for each fuel model specified in the SIMULATION file.

The variable **fuelID** is a unique identification number for this fuel model that can be used to identify the 13 Anderson (1982) fuel classes or any other fuel model classification. The next set of parameters represents the eight fuel components of dead fuel. The parameters are particle density (**rhop_dead**), heat content (**lhv_dead**), surface area to volume ratio (**mps_dead**), fuel moisture at time of fire (**moist_dead**), and percent fuel consumption at the time of fire (**consume_dead**). The same five variables are used to describe the live fuel components (**rhop_live**, **lhv_live**, **mps_live**, **moist_live**, and **consume_live**). The variables **MXDEAD** and **MXLIVE** are set at a value of 8 inside the FireBGCv2 program and are not allowed to vary.

The next set of three parameters are used to describe general characteristics about the live and dead fuels, which means there are only two values per line rather than eight. The variable **mext** is the moisture of extinction of live and dead fuels, **fuel_bulk** is the fuel bulk density of the live and dead fuel beds, and **om_bulk** is the bulk density of only litter and duff.

The last three parameters describe some general information on the fuel model as a whole (that is, only one value per parameter). The **fuel_depth** variable is the depth of the fuel bed. The **scm** and **wndfc** variables are the spread component and wind reduction factor in the NFDRS fire model parameters used to compute fire danger ratings in the model. The following is a sample of a Fuel.in file:

```
FUELS This file contains the fuel model parameters for FireBGCv2 applications
Fuel Comp       Duff     Litter    1 hour    10 hour    100 hr    1000 hr     Shrub       Herb

                                  1 Fuel Model Number - Low elevation FBM 8
rhop-dead            0.550        0.510       0.390       0.390       0.390       0.390       0.510        0.510
lhv-dead         18586.7      18586.7     18586.7     18586.7     18586.7     18586.7     18586.7      18586.7
mps-dead           111.0         57.410      61.16       11.760       2.880       0.980       3.156       91.8560
moistdead            0.60         8.000       0.060       0.080       0.100       0.150       0.1000       0.0500
consume-dead         0.90         0.900       0.950       0.845       0.845       0.790       0.9000       0.9900
rhop-live            0.550        0.510       0.390       0.390       0.390       0.390       0.513        0.513
lhv-live         18586.7      18586.7     18586.7     18586.7     18586.7     18586.7     18595.0      18595.0
mps-live           111.0         57.410      61.166      11.760       2.880       0.980      49.200       91.860
moistlive            0.60         8.000       0.060       0.080       0.100       0.150       0.800        0.500
consume-live         0.90         0.900       0.900       0.800       0.500       0.010       0.900        0.900
mext                 0.300        0.300
bulk-d/l             0.0115       0.001
duflitbulk          76.9         44.1
fdepth               0.06
spreadcomp           1.0
windmultfactor       1.0
```

Site.in File

This is a vertically cycling, descriptive file that repeats for each site specified on the landscape. Each site is defined as a unique biophysical setting where weather, soils, and potential vegetation characteristics are specified as static variables for the FireBGCv2 simulation. This biophysical setting is usually taken from a digital map that delineates settings by topography, soils, weather, and landform. The site is a very important construct in FireBGCv2 because it is used to represent biophysical processes unique to the stands within each site, such as weather, soils, and fire regime. It is suggested that the mapping of sites use the biophysical settings that represent potential vegetation (habitat type groups, for example) to delineate each site because, that way, the parameterization of the Species.in and Tree.in files will be easier. Create the site map using any number of multivariate statistical analyses such as clustering, discriminant analysis, or regression trees; however, be sure that the final site map matches the final stand map in terms of its biophysical setting. For example, you should not have a stand that has lodgepole pine on a dry ponderosa pine site type. Assign to each stand a

site ID once the site map is created. Each site in the Site.in file is specified by the following parameters:

Rec	Variable	Description	Units
1	Title	Title line for site file	none
		These fields are cycled for each site	
1	NONE	This is a record to identify or label the site	none
2	id Site	ID number ID	number
3	biomeID	Biome ID number 1-evergreenforest, 2-deciduous forest, 3-shrubland, 4-grass	code
4	nstands	Number of initial stands at start of simulation	number
5	fuelID	Fuel model ID number for this site ID	number
6	plantID	Understory plant model ID number for this site ID	number
7	prate	Treatment priority rating by site	rating
8	weather_file	Weather filename for the site--up to 128 characters	filename
9	wind_speed	Ave annual wind speed	m s^{-1}
10	wind_dir	Ave annual wind direction	degrees
11	latitude	Latitude of site	decdeg
12	elev	Elevation of site	m
13	albedo	Default site albedo	dim
14	maxlai	Maximum leaf area index (all sided)	m2 m^{-2}
15	maxba	Maximum stand basal area	m2 ha^{-1}
16	siteindex	Site index at year 50	m
17	spm	Maximum number of seedlings per unit area	seed m^{-2}
18	seed_lag	Number of lag years for establishment after fire	years
19	fire_freq	Average fire frequency	years
20	fire_size	Average fire size	ha
21	soil_depth	Depth of soil (free rooting zone)	m
22	sand	Percent sand in soil profile for soil depth	percent
23	silt	Percent silt in soil profile for soil depth	percent
24	clay	Percent clay in soil profile for soil depth	percent
25	volN	Fraction nitrogen loss that is volitalized	proportion

The site **id** number is a unique identification number for this site. The **biomeID** number is a flag that identifies whether the site can support evergreen forests (option 1), deciduous forest (option 2), shrublands (option 3), or grasslands (option 4). The **nstands** variable indicates the number of stands that are located within each site. The **fuelID** and **plantID** numbers reference the fuel and plant model identification numbers that are defined in the Fuel.in and Plant.in files, respectively. The variable **prate** is used to rate the site for prescribed burn and harvest treatments according to which sites should be treated first and last. The **weather_file** is a full pathname of the file that contains the daily weather for this site. The format for this file is Julian date, minimum temperature (°C), maximum temperature (°C), and precipitation (cm). The **wind_speed** and **wind_direction** variables store the average wind speed (m/sec) and wind direction (azimuths) for fire spread and some evapotranspiration calculations.

The **latitude**, **elevation**, and **albedo** of the site can be taken from digital spatial datasets such as DEMs and thematic map layers, or they can be assigned from paper maps. The **latitude** is in decimal degrees, the **elevation** is the average elevation of the site above mean sea level. The **albedo** is for the site at near climax conditions.

The next set of parameters defines the potential productivity of the site. The **maxlai** is the maximum leaf area index that the site can support. The **maxba** is

the maximum basal area ever to occur on this site or the potential basal area for this site. The **siteindex** is the site index of the trees for the site; the site index is the height of the trees at 50 years. The variable **spm** is the maximum number of seedlings per meter on this site. The **seedlag** is the time it takes in years to ameliorate site conditions so that successful regeneration is possible. The seedlag at high elevations can sometimes exceed 20 to 50 years. The **fire_freq** is the average fire return interval (years) for this site based on fire history evidence. Last, **fire_size** is the average size of individual fires within this site based on observed data.

The last set of parameters quantifies site soil conditions. The **soil_depth** is the average depth of the free-rooting zone across the site in meters. The variables **sand**, **silt**, and **clay** identify the average percent sand, silt, and clay of the soil profile defined by the soil depth. These four parameters can be taken from digital soils databases such as STATSGO (http://soils.usda.gov/survey/geography/statsgo/). Last, the **volN** variable specifies the fraction of nitrogen in the downed wood, litter, duff, and logs that is lost to the site via volatization to the atmosphere. This parameter can be found in various fire publications.

Stand.in File

The stand file is a horizontal, cycling, descriptive file that contains important stand-level ecosystem information that is critical for FireBGCv2 parameterization and initialization. This file is also a little more complex than the others in that the width of the file (number of fields on one line) varies by the number of undergrowth guilds for the plantID model specified in the Site.in file. The first line of the file is the title line where anything can be written to describe this file. The second line is a column header line for ease of entering data. The remaining lines have the following format:

Variable	Field	Size	Description	Units
siteID	1	5	Plot site ID number	none
standID	2	10	Plot stand ID number	none
ntree	3	5	Number of trees in stand	number
elev	4	10.4	Ave elevation for stand	m
slope	5	10.4	Ave slope for stand	percent
aspect	6	10.4	Ave aspect for stand	degrees azimuth
snowW	7	10.4	Snow water	kg m^{-2}
soilW	8	10.4	Soil water	kg m^{-2}
litter	9	10.4	Litter biomass	kg m^{-2}
duff	10	10.4	Duff biomass	kg m^{-2}
1hr	11	10.4	Down woody 1 hr biomass	kg m^{-2}
10hr	12	10.4	Down woody 10 hr biomass	kg m^{-2}
100hr	13	10.4	Down woody 100 hr biomass	kg m^{-2}
1000hr	14	10.4	Down woody 1000 hr biomass	kg m^{-2}
guild1	15	10.4	Undergrowth guild 1 biomass	kg m^{-2}
guild2	16	10.4	Undergrowth guild 2 biomass	kg m^{-2}
guild3	17	10.4	Undergrowth guild 3 biomass	kg m^{-2}
guildn		10.4	Undergrowth guild n biomass	kg m^{-2}

The **siteID** identifies the biophysical setting of this stand, and the site ID number is specified in the Site.in file. The **standID** is a unique identification number that is assigned to this stand. It is important to note that all of the stand IDs specified in the Stand.in file must appear on the initial stand map (see the "Map.in File" section). The variable **ntree** specifies the number of trees (living and dead) on the stand. This variable is used to read the details of these trees (DBH, height,

age, etc.) from the Tree.in file. The **elev**, **slope**, and **aspect** variables describe the average elevation (m), slope (%), and aspect (az) of the stand. The beginning snow water (water in the snowpack) and soil water (kgW m^{-2}) are specified in the variables **soilW** and **snowW**.

The remaining fields are used to define the biomass on the forest floor. The biomass in the duff and litter layers is specified in the variables **duff** and **litter**. Downed woody fuel (coarse and fine woody debris) is divided into four size classes: **1hr** (0 to 0.5 cm diameter), **10hr** (0.5 to 2.5 cm), **100hr** (2.5 to 7.0 cm) and **1000hr** (>7.0 cm).

The live biomass in the undergrowth guilds is specified in the last set of variables. The number of fields must correspond to the number of guilds in the plant model specified in the Site.in file. These will be stretched horizontally across the Stand.in file so the file width could be quite wide. Each stand in the simulation landscape is assigned a site ID number, as described in the "Site.in File" section. Sites are identified by individual site ID numbers and represent unique biophysical settings on the simulation landscape.

Tree.in File

The tree file is a cycling, horizontal, descriptive file that specifies all of the trees in a simulation plot that represents a stand. Various silvicultural metrics are recorded for each group of trees. These data reflect a list of all trees within the reference stand. These data can be taken from one plot and entered as a tree list for the entire plot, or they can be summarized across a stand so that the tree silvicultural measurements are roughly an average for all trees in a size class. It is important that the number of trees in a stand correspond to the number of trees entered here.

A list of trees must be assigned to each stand and site combination using field data. This is done by summarizing the stand and site combinations from the maps (lodgepole pine sapling stand type on an upper subalpine site type, for example) into a table. Then, the available field data should be summarized in a similar manner. Finally, choose the field plot that best represents each stand-site combination and assign the sampled tree characteristics to that stand-site combination in this format of the Tree.in file:

Variable	Field	Size	Description	Units
siteID	1	5	Site ID number	none
standID	2	10	Stand ID number	none
treeID	3	5	Tree ID number	None
sppID	4	5	Tree species 4-character code	code
stat	6	5	Tree health (1-healthy, 4-snag)	none
tdens	5	10.1	Tree density	t ha^{-1}
dbh	7	10.1	Tree DBH	cm
ht	8	10.1	Tree height	m
hbc	9	10.1	Height to base of crown	m
age	10	10.1	Tree age	years

The **siteID** number corresponds to the **siteID** in the Site.in file; the **standID** corresponds to the **standID** in the Stand.in file; the **treeID** is an ID number for this tree; and the **sppID** is the four-letter species code that is identified in the Species.in file. The variable **stat** is tree status; there are only two status codes: 1 is a live tree and 4 is a snag. The variable **tdens** is tree density on the plot. Variables **dbh**, **ht**, **hbc**, and **age** are average diameter, height, crown height, and age for this tree class or actual values for this tree. Trees are best entered as a list in this

format, in which case the **dbh**, **ht**, **hbc**, and **age** would be actual sampled values for that tree. For simplicity the user can enter trees as diameter classes with the midpoint of the diameter class as the **dbh** and the average height, crown height, and age as **ht**, **hbc**, and **age**. The trees are entered in sequence by their ID numbers by stand and then by site.

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Index of Variables

Page

14 $BULK_l$

Bulk density of litter (kg m^{-3})

Bulk density of the litter (kg m^{-3})

15 CAREA

Canopy area of all trees in the stand (m^2)

15 CC

Percent canopy cover of all trees in the stand (%)

52 CF

Consumption factor input to model (proportion)

65 CK

Scorched tree crown volume (%)

49 CL

Tree crown length (m)

14 CONSUME

Proportion of fuel that will be consumed in the fire (proportion)

52 ConsumeC

Amount of fuel consumed across all components (kgC m^{-2})

41 c_p

specific heat of air (1010.0 J kgW K^{-1})

49 CPLA

Cumulative projected leaf area (m^2)

65 CS

Length of crown that is scorched (m)

14 DBH

Diameter at breast height (cm)

60 DD

Days that daytime temperature is above 2 °C

60 DD_{max}

Maximum number of degree-days for a species to account for temperature effects on tree growth

60 DD_{min}

Minimum number of degree-days for a species to account for temperature effects on tree growth

60 DD_{opt}

Optimum number of degree-days for a species to account for temperature effects on tree growth

16 DeadcrootC

Dead coarse root carbon at stand or tree level (kgC)

16 DeadstemC

Dead stem or heartwood carbon at stand or tree level (kgC)

57 DEPTH

Depth of litter and duff layer (cm)

60 DINC

Diameter increment for tree growth in a year (cm)

Page

60 $DINC_{max}$
Maximum possible diameter increment for tree growth (cm)

24 DIST
The distance between the seed source pixel and target pixel (m)

34 D_l
Daylength (seconds)

43 DLMR
Daytime respiration of sun/shade leaves per projected leaf area

13 DSR
Days since last rainfall (days)

13 DSS
Days since last snowfall (days)

16 DuffC
Amount of carbon in the duff on the forest floor (kgC m^{-2})

46 DWTF
Turnover fraction specified by species in the Species.in file

53 EF
Emission factor (kg consumed kg^{-1} of smoke element)

41 ELEV
Stand elevation (m)

48 EMC
Equilibrium fuel moisture content (%)

34 EPPT
Effective daily precipitation (kgW m^{-2})

39 ET
Evapotranspiration (kgW m^{-2})

39 EVAP
Evaporation (kgW m^{-2})

18 FDEAD
Fraction of guild biomass that is dead at the time of a fire

14 FDEPTH
Fuel depth (m)

65 FI
Fire intensity (kw m^{-1})

28 FIRESIZE
Size of a simulated fire (m^2)

26 FIRESUPP
Index that ranges from 0 (no suppression) to 1 (total suppression)

46 FLBC
Fraction of that biomass that is carbon

43 FLNR
Fraction of leafN in Rubisco

48 FM_{max}
Maximim foliar fuel moisture for tree crowns (%)

Page

48 FM_{min}
Minimum foliar fuel moisture for tree crowns (%)

13 FRI
Average fire return interval for a point in a site (years)
Fire return interval or number of years between fire for all land area within a site (years)

16 FrootC
Fine root carbon at stand or tree level (kgC)

56 $FROST_{fall}$
Earliest acceptable fall frost (yearday)

56 $FROST_{spring}$
Last acceptable spring frost (yearday)

13 FSIZE
Average fire size (ha)

18 FUELID
Fuel ID number referenced in the Fuel.in file

39 g_l
Leaf-level stomatal conductance (kgW sec^{-1})

39 g_{max}
Maximum stomatal conductance (kgW sec^{-1})

41 GS
Standard gravitational acceleration (9.80665 m sec^{-1})

34 GS_{mid}
Midpoint of the growing season (yearday)

15 $HABSUIT_k$
Habitat suitability index for wildlife species *k*

15 HBC
Height to base of crown (tree) or canopy (stand) (m)

50 $HERB_{dead}$
Dead herbaceous fuel component loading (kgB m^{-2})

36 $HERB_{PPT\_GREENUP}$
Critical threshold for herbaceous greenup based on precipitation (kgW m^{-2})

36 $HERB_{TEMP\_GREENUP}$
Critical threshold for herbaceous greenup based on soil temperature (°C)

33 H_r
Relative humidity for a day (%)

48 HSIZE
Thickness of a canopy layer (m)

15 HT
Stand height or average height of all trees in the overstory (m)
Tree height or stand height (m)

40 k
Extinction coefficient

26 KBDI
Keetch Byram Drought Index

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26 $KBDI_{base}$
Mean across all years of the maximum KBDI value for one year

46 kFRAG
Base fragmentation rate for decomposition

15 LA
Leaf area of the canopy or tree (m^2 m^{-2})

13 LAG
Number of years after a fire before regeneration can occur (years)
Number of years after a fire before tree regeneration (year)

13 LAI_{max}
Maximum projected leaf area index for the site (m^2 m^{-2})

34 LAT
Latitude (degrees)

7 LeafC
Leaf carbon at either stand or tree level (kgC)

16 $LeafC_{max}$
Maximum leaf carbon at stand or tree level in one year (kgC)

16 LeaffallC
This year's leaf fall that hits the ground (kgC m^{-2})

18 $LEAF_{frac}$
Fraction of guild biomass that is leaf. This is the proportion of the total biomass that is leaf biomass

46 LFRAC
Fraction of undergrowth biomass that is leaf (proportion)

14 LHV
Heat content of fuel (BTUs)

16 LitterC
Amount of carbon in litter on the forest floor (kgC m^{-2})

16 LivecrootC
Live coarse root carbon at stand or tree level (kgC)

16 LivestemC
Live stem or bole carbon at stand or tree level (kgC)

43 LNC
Leaf nitrogen concentration per unit projected leaf area calculated as 1 / PSLA

48 MC_{foliar}
Foliar moisture content (%)

14 MOIST
Fuel moisture at the time of fire expressed as a proportion of dry weight (proportion)

14 MPS
Surface area to volume ratio (m^2 m^{-3})

42 MR
Maintenance respiration (kgC)

43 MRP
Maintenance respiration coefficient

Page

48 MXHGT

Maximum number of canopy layers (number)

34 NETPPT

The net precipitation (inches) as computed from the previous and current day's rainfall (inches)

13 NFREEZDAY

Number of freezing days in the year (>-30 °C) (days)

28 NFREEZDAYS

Number of days below 20 °C (days)

13 NFROZDAY

Number of frozen days in a year (>-40 °C) (days)

28 NFROZDAYS

Number days below 40 °C (days)

23 NOCROP

Number of years to block a cone crop after a good crop (years)

Years before another cone crop is possible (years)

39 OutflowW

Excess water that is drained off the stand via runoff or subsurface flow (kgW m^{-2})

41 p_a

Air density

34 PAR

Photosynthetically active radiation

37 PAREA

Simulation plot area (m^2)

63 P_{beetle}

Probability of tree mortality from mountain pine beetle

47 PCELL

Proportion of wood that is cellulose

23 PCONE

Probability of a good cone crop (probability 0 to 1)

24 P_{dist}

Probability of a seed landing on a pixel

26 P_{fire}

Probability of a fire

Probability of tree mortality from wildland fire

48 PLA

Projected leaf area of the tree or canopy (m^2 m^{-2})

15 PLAI

Projected leaf area index (m^2 m^{-2})

40 PLAISHADE

Projected leaf area index of shaded leaves (m^2 m^{-2})

40 PLAISUN

Projected leaf area index for sunlit leaves (m^2 m^{-2})

47 PLIG

Proportion of wood that is lignin

Page

40 PPFD

Photon flux density of sun/shade leaves

40 $PPFD_{50}$

PAR photon flux density (umol sec^{-1}) needed to open 50 percent of the stomata

40 $PPFD_{plai}$

PAR photon flux density per unit of projected leaf area index

32 PPT

Daily precipitation (cm in input, kgW m^{-2} in model)

62 P_{random}

Probability of tree mortality from random events

63 P_{rust}

Probability of tree mortality from white pine blister rust

56 pSEROT

Probability of serotiny of lodgepole pine

16 PSN

Amount of carbon from photosynthesis at stand or tree level (kgC)

56 P_{sprout}

Probability of sprouting

62 P_{stress}

Probability of tree mortality from stress

39 r_c

Correction factor for temperature and pressure for stomatal conductance

26 rCLIMATE

Reduction factor that scales ignition probabilities to climate signal (0 to 1 value, dimensionless)

60 rCROWD

Reduction factor to account for the effect of crowding or resource availability in tree growth

56 rDENS

Density reduction factor for regeneration

58 rDIST

Reduction factor for regeneration accounting for seed dispersal distance

56 rDSUR

Reduction factor for seedling survival in duff

26 REBURN

Number of years before a stand can burn again (year)

16 RESP

Amount of carbon from respiration at stand or tree level (kgC)

26 rFIRE

Reduction factor that scales fire ignition probabilities to account for size of stand (0 to 1, dimensionless)

14 RHOP

Fuel particle density (kg m^{-3})

Page

26 rMGT

Reduction value that scales fire ignition probabilities to level of suppression effecicacy (0 to 1, dimensionless)

6 RNUM

Random number between 0.0 and 1.0 (dimensionless)

Random number returned from the random number generator

39 rPPFD

Scalar that represents light effects on stomatal opening

41 RR

Gas law constant (8.3143 m^3 Pa mol^{-1} K^{-1})

40 rSHADE

Proportion of photon flux density to the shaded leaves

46 rSOILT

Soil temperature scalar for decomposition

46 rSOILW

Soil water scalar for decomposition

39 rSWP

Reduction factor for soil water potential effects on conductance

39 rTEMP

Reduction factor to account for the effect of temperature on tree growth

6 rTREE

Reduction factor accounting for number of cone producing trees in a stand (0 to 1, index)

13 RUST

Flag indicating if this tree is rust resistant

Rust infection flag (0-no, 1-yes)

13 $RUST_{rh}$

Average humidity in September (%)

13 $RUST_{temp}$

Average temperature in September (°C)

59 rWATER

Reduction factor to account for the availability of water

40 SALBEDO

Stand albedo with snowpack

13 SAP_{max}

Maximum number of saplings per meter to be established in the simulation plot (sap m^{-2})

Maximum number of saplings that can regenerate in any one year across all species (saplings m^{-2})

40 SDECAY

Snow albedo decay coefficient

25 SEEDOPT

Simulation option number of simulation years before seed dispersal is updated (year)

15 $SEEDTREE_i$

Number of cone producing trees for species *i*—trees>10 cm DBH, >min reproductive age (trees)

Page

51 SH
Scorch height (m)

50 $SHRUB_{dead}$
Dead shrub fuel component loading (kgB m^{-2})

53 SMOKE
Smoke emissions by factor (kg)

34 SnowW
Snowpack (kgW m^{-2})

16 SoilC
Amount of carbon in mineral soil on the forest floor (kgC m^{-2})

27 SPIX
Number of pixels to spread the fire in one time step (pixels)

18 SppID
A species ID number referenced in the Species.in file

56 $SPROUT_{max}$
Maximum sprouting potential (sprouts)

32 SRAD
Net daily canopy shortwave radiation (W m^{-2} day^{-1})

40 STDA
snowpack temperature deficit (°C)

16 StemC
Total live and dead stem carbon at stand or tree level (kgC)

20 STRESS
Years of stress (years)

42 SW
Stand-level shortwave radiation (W m^{-2} day^{-1})

46 sW1 to sW1000
Decomposition scalars for woody particle size for 1 hr to 1000 hr woody fuels

42 SWABS
Absorbed shortwave radiation (W m^{-2} day^{-1})

42 SWREF
Reflected shortwave radiation (W m^{-2} day^{-1})

35 T_{aaave}
average annual daily average temperature (°C)

33 T_{day}
Daytime temperature (°C)

34 T_{dew}
Dewpoint temperature (°C)

35 TGOD
Tree greenup onset date (Julian date)

65 T_{kill}
Lethal temperature for tree foliage (assumed as 60 °C)

32 T_{max}
Maximum daily temperature (°C)

Page

33 T_{min}
Minimum daily temperature (°C)

33 T_{night}
Nighttime daily temperature (°C)

33 T_{soil}
Daily soil temperature (°C)

44 UBIOMASS
Undergrowth biomass (kgB m^{-2})

44 $UBIOMASS_{max}$
Maximum undergrowth biomass for a guild (kgB m^{-2})

44 UGROWTH
Undergrowth growth by guild (kgB m^{-2})

19 UHT
The instantaneous height of the undergrowth guild (m)

18 UHT_{max}
Maximum undergrowth guild height (m)

19 ULA
The instantaneous projected leaf area of the undergrowth guild (m^2)

19 UNPP
The amount of carbon gain as growth for that guild during that year (kgC m^{-2})

19 UPSN
The amount of carbon from photosynthesis for that guild during that year (kgC m^{-2})

19 URESP
The amount of carbon lost from respiration for that guild during that year (kgC m^{-2})

49 USLA
Undergrowth specific leaf area (m^2 kgC^{-1})

38 VMC
Soil water content (%)

38 VMC_{sat}
Soil volumetric water content (percent)

32 VPD
Vapor pressure deficit (Pa)

39 VPD_{close}
Vapor pressure deficit for closing stomata, as specified by species (MPa)

39 VPD_{open}
Vapor pressure deficit for opening stomata, as specified by species (MPa)

16 W1000C
Amount of carbon in logs (1000 hr woody) on the forest floor (kgC m^{-2})

16 W100C
Amount of carbon in large branches (100 hr woody) on the forest floor (kgC m^{-2})

16 W10C
Amount of carbon in branches (10 hr woody) on the forest floor (kgC m^{-2})

16 W1C
Amount of carbon in twigs (1 hr woody) on the forest floor (kgC m^{-2})

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34	YD	Yearday or Julian date
26	YSB	Years since last fire (year)
20	YSI	Years since mountain pine beetle epidemic (years)
41	λ	Latent heat of vaporization
38	Ψ	Soil water potential (MPa)
40	Ψ_{close}	soil water potential for stomatal closing (MPa)
40	Ψ_{open}	soil water potential for stomatal opening (MPa)
38	Ψ_{sat}	Soil water potential at soil saturation (MPa)

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