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A Comparison of Coarse Scale Fire Effects Simulation Strategies

Abstract

Development of management-oriented computer models for coarse scale fire simulation is often problematic because of the tradeoff between prediction realism and model utility. This study compares three spatial modeling strategies of increasing complexity for simulating coarse scale succession and fire dynamics across the 80 million ha Interior Columbia River Basin (ICRB). In all three approaches successional dynamics are modeled using a multiple pathway approach where seral community types, called succession classes, are linked along pathways that converge to a stable community type called a potential vegetation type which represents a unique biophysical setting that is static throughout a simulation. Fire dynamics are simulated using three stochastic approaches implemented in three separate computer models. The Columbia River Basin succession Model (CRBSUM) simulates fire using probabilities from a uniform probability distribution that reflects a representative fire return interval. CRBSUM was modified to create CRBSUM2 that simulates fire occurrence at the potential vegetation type level and subsequent fire effects at the successional class level. The FIREPAT (FIRE PATtern) model stochastically simulates fire starts from a three parameter Weibull function. Fire is then spread across the landscape using a cookie-cutter approach where an exponential probability function determines the size of an ellipse wherein all pixels will be burned. Simulated landscape patterns and disturbance results are compared across the three approaches. Results indicate models of increasing complexity require additional parameterization and computer time, but provide more realistic results.

Introduction

Realistic fire patterns are often difficult to simulate in spatially-explicit, coarse scale vegetation succession models because of scale conflicts (Baker 1989, McKenzie et al. 1996a, McKenzie 1998). The fine scale characteristics that dictate fire spread, intensity and direction, such as topography, fuel moistures, and wind, are not accurately represented at coarse scales because of the low resolution of input data layers (Prentice et al. 1993, Wiens 1989). Moreover, wildfires usually burn in a mosaic of intensities and spread rates that is difficult to simulate when pixel sizes are large and spatial data layer categories are broadly defined (McKenzie 1998). As a result, many coarse scale modeling efforts do not directly simulate fire dynamics, but instead predict subsequent fire effects based on vegetation and site characteristics (Chew 1996, McKenzie et al. 1996a, Lenihan et al. 1998). The problem with this approach is that it is difficult to predict where and how hot a fire would have burned on the simulation landscape without knowing fire behavior and growth characteristics. Simulation of the spread of fire from one pixel to another (i.e., contagion) becomes problematic when all the factors that govern fire growth are unknown and the underlying mechanistic processes are not modeled such as in coarse scale fire simulations (McKenzie et al. 1996a, Lenihan et al. 1998).

Design of most fire models created for management application requires a realistic simulation of fire dynamics but at a complexity readily understood by fire managers. This fundamental modeling challenge is to balance algorithm simplicity with observed reality. Coarse scale fire models that produce accurate simulations of fire spread and shape may require parameters that managers find difficult to understand and quantify. The fine scale fire growth model FARSITE (Finney 1994) requires eight spatial data layers and two hourly weather files which many fire managers may find difficult to create or obtain for their lands (Keane et al. 1998). Some models may require simplistic parameters but need so many that quantification is a laborious task. The CRBSUM model (Keane et al. 1996a) uses input parameters that are easily estimated, but requires stratification of these parameters across so many geographic regions, potential vegetation types, cover types and structural stages that parameterization is sometimes difficult for large land areas. The utility of any fire model is directly related to the user's ability to understand and use it, and to interpret its output. Land managers may find output from the event-driven, grid-based stochastic simulation model EMBYR (Gardner et al. 1996) easy to understand but difficult to interpret because of its stochastic percolation approach. Still other models realistically simulate fire effects using detailed mechanistic approaches, but their application to management problems is difficult because quantification of input parameters and initial conditions requires a high level of expertise (Keane et al. 1996b, see Landsberg and Gower 1997).

Several approaches have been used to model disturbance contagion on fine and meso scale landscapes. Turner and Romme (1994) and Gardner et al. (1996) used a stochastic cellular model to simulate the spread of crown fires in Yellowstone National Park. Many other cell automata models have been used to simulate stand-replacement fires in the central Rocky Mountains and Southwest (Ball and Guertin 1990, Vasconcelos and Guertin 1992). Stochastic percolation techniques (Beer and Enting 1990, Von Niessen and Blumen 1988) are used to reflect the uncertainty of fire behavior across a heterogeneous landscape. Clarke et al. (1994) used fractal algorithms to propagate fire through a landscape matrix. Finney (1994) and Coleman and Sullivan (1997) use mechanistic fire behavior algorithms to compute intensity and spread of fires in a spatial domain. Unfortunately, the application of these models to coarse scale landscapes becomes enigmatic because the underlying processes that contribute to fire spread are best simulated at finer scales. In addition, the parameterization of such coarse scale models is difficult because of the complexity and diversity of coarse scale landscapes which contain many ecosystems, biophysical environments, and disturbance regimes.

Most coarse scale fire effects and succession models stochastically simulate disturbance processes and model succession using a deterministic pathway approach (McKenzie et al. 1996b, Keane et al. 1996a). These models are often designed for simplicity because coarse scale landscapes are defined by low resolution maps described by broad vegetation classifications. Because these models are used to investigate potential impacts of various management strategies, they must be built so input parameters are easily quantified and output results are easily understood. The addition of detailed contagion properties to disturbance simulations would increase parameterization complexity and make it more difficult for research and management to use and interpret (Landsberg and Gower 1997).

This paper compares three coarse scale fire modeling approaches for simplicity, accuracy, and realism based on simulated fire distribution, fire pattern, and landscape composition. These models do not directly simulate fire behavior but instead infer fire dynamics and subsequent effects from the biophysical environment and vegetation characteristics described for each pixel on the simulation landscape. All models use the Interior Columbia River Basin (ICRB) as it appeared around the late 19th century as the simulation area (Figure 1). A major assumption of this comparison is that these models will eventually be used in land management applications, so model input must be easily quantified and output must be readily understood by land managers. Results from this comparison will aid future development of coarse scale fire effects simulation models and improve understanding into the relationship between simulation complexity and model utility.

Model Overview

Three computer models of increasing complexity are compared in this study. All three models simulate succession using the deterministic, multiple pathway approach taken directly from CRBSUM (Columbia River Basin SUccession Model), the model used to simulate landscape changes for the Interior Columbia Basin Ecosystem Management Project (ICBEMP) (Keane et al. 1996a, Quigley et al. 1996). The successional framework of CRBSUM is a variation of the conceptual fire succession modeling approach presented by Kessell and Fischer (1981). This approach links seral vegetation communities along multiple pathways of successional development (Hironaka 1989, Elliot et al. 1993) (Figure 2). All pathways will eventually converge to a unique "stable" or "climax" plant community called a Potential Vegetation Type (PVT) (Arno et al. 1985, Pfister et al. 1977, Steele and Geier-Hayes 1989). A PVT is the endpoint of the successional pathway diagram and identifies a unique biophysical setting that supports a distinctive plant community (Arno et al. 1985, Steele and Geier-Hayes 1989). Coarse-scale PVT's for the ICRB were created by grouping similar habitat type and plant

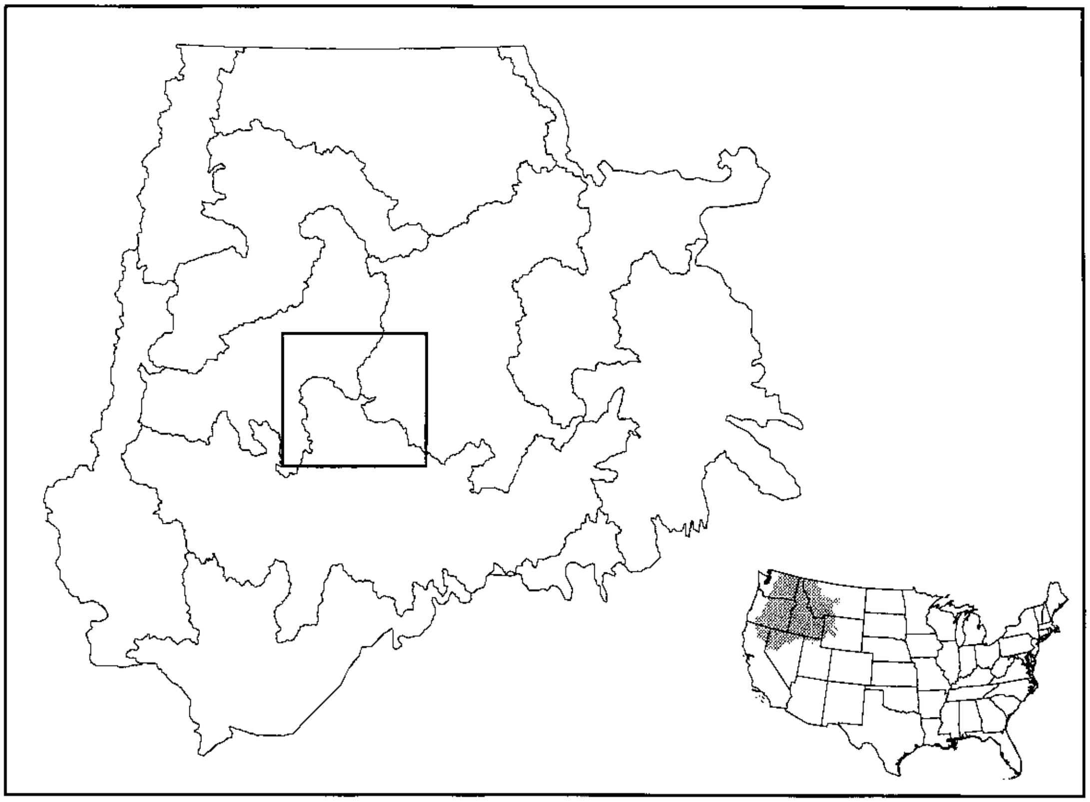

Figure 1. The Interior Columbia River Basin (ICRB) simulation area with the ten geographic regions used in this study. Box in the western edge of the ICRB identifies an area used to investigate patch dynamics in this study.

associations based on climate, topography, disturbance regimes, and geomorphology (Reid et al. 1995). There is a unique set of successional pathways for each PVT present on the simulation landscape and PVT delineations do not change through time.

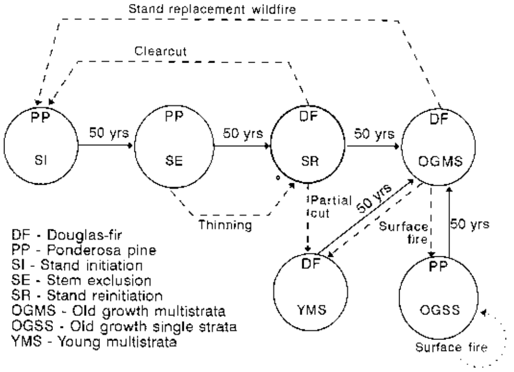

Figure 2. Successional pathway diagram for a theoretical Douglas-fir Potential Vegetation Type (PVT). Disturbance effects are shown by the dashed lines.

Succession class is the term used to describe a vegetation community in this pathway approach, and each succession class is described by a cover type and a structural stage (Figure 2). The time spent in a succession class depends on the shade-tolerance and lifespans of the dominant species (Cattelino et al. 1979, Noble and Slatyer 1977). Cover types are named for the vascular plant species having the plurality of canopy cover for range types (Shiflet 1994) or for the tree species having the greatest basal area for forest types (Eyre 1980). Structural stages represent developmental changes in a plant community's structure described by the vertical distribution of plant sizes and cover (Oliver and Larson 1990). The original Oliver and Larson (1990) process-driven structural stages were modified by O'Hara et al. (1996) to account for the influence of natural and anthropomorphic disturbances on successional development in forest and woodland types. Villnow

(1995) developed structural stages for rangelands that were later revised for coarse-scale applications (Keane et al. 1996a).

The three models differ in their treatment of disturbance, specifically fire. Disturbances disrupt successional development and can delay or advance the time spent in a succession class, or, more commonly, cause an abrupt change to another succession class (Figure 2). Disturbance is simulated as a stochastic process defined from user-specified probability parameters. Disturbance probabilities can be stratified by geographic region, PVT and succession class. Each of the three models use some variation of this method to simulate fires on the coarse scale landscape.

Columbia River Basin Succession Model (CRBSUM)

CRBSUM is a spatially explicit, deterministic vegetation dynamics simulation model that incorporates disturbance as a simple stochastic process (Keane et al. 1996a). Successional development on a pixel (small portion of the landscape) is modeled as a change in structural stage and cover type (i.e., succession class) keyed to successional time simulated at an annual time step. Occurrences of human-caused and natural disturbances are stochastically simulated at the pixel-level from a set of probabilities that describe a land use policy or management plan. A random number from an uniform probability distribution is generated, and if the number is less than the probability of fire for a pixel, a fire is simulated. Disturbance effects are deterministically modeled as an immediate change in structural stage and/or cover type with a corresponding adjustment of the successional clock. The model generates several output maps and data files that describe the simulated landscape at each time step.

CRBSUM2

Two major limitations to CRBSUM are that it does not contain routines that explicitly simulate disturbance and disturbance effects at multiple scales, and it does not incorporate the relationship of surrounding pixels into the simulation of disturbances. Successional development and disturbance effects are modeled pixel-by-pixel using uniform random number distributions. As a result, fire-disturbed pixels are often uniformly distributed across the simulation landscape in a "salt and pepper" pattern. Additionally, simulation results often have low year-to-year variation for simulated fire-burned areas because of the homogeneous distribution of fire in space and time. Surrounding pixels are not burned in one fire event and nearly the same number of pixels are burned each year, which is an unrealistic representation of fire dynamics. Actual coarse scale fires often burn in large contiguous patches, and annual fluctuations in burned areas can be quite large due to the large spatial and temporal variability in drought and wind (Alvarado et al. 1998; Lertzman et al. 1998). CRBSUM does not account for these fluctuations and therefore seems to underestimate the range of variability in fire occurrence and spread. CRBSUM2 was created to keep the simplistic structure of CRBSUM but improve the spatial and temporal simulation of fire processes.

Fires are simulated at two organizational scales within the CRBSUM2 structure. The occurrence of fire is simulated at the region-PVT level while the fire's effect is simulated at the succession class level (cover type and structural stage). Fire occurrence probabilities are stratified by PVT and geographic region (see Figure 1) to improve the level of detail in input data layers. A random number is generated from a uniform probability distribution and compared with user-specified fire occurrence probabilities for a PVT within a region. If the random number is below the occurrence probability, a fire is simulated and all pixels within that PVT and geographic region are considered to experience a fire. The effect of that fire on the pixel's cover type and structural stage is simulated at the succession class level for that PVT and region. Each succession class contains user-specified probabilities for three different types of fires—surface fire, mixed fire, and stand-replacement fire. Another random number is generated and compared to these three probabilities to determine the type of fire that the pixel will experience, and this, in turn, dictates the resultant post-fire succession class and succession age. Some PVT-succession class combinations have no chance of any type of fire (all probabilities are zero), such as a rocklands or lakes, and no fire effects are modeled.

FIRE PATtern Succession Model (FIREPAT)

A problem with both CRBSUM and CRBSUM2 is their inability to simulate realistic fire patches on the landscape. CRBSUM2 is an attempt to retain the simplicity of CRBSUM by indirectly modeling contagious burning across adjacent pixels using a multiple scale approach across two vegetation classifications. However, this approach confines the fire to static PVT-region boundaries and the subsequent effects can again appear in a random-scatter pattern within the PVT borders. A more mechanistic treatment of fire spread across a coarse scale landscape may be intractable or impractical because the causal mechanisms of fire spread cannot be translated to coarse scales and the input parameters needed for mechanistic models may be difficult to quantify and understand for coarse scale vegetation classifications. FIREPAT is an attempt to bridge the gap between mechanistic and stochastic approaches by simulating fire ignition and size to compute the number of contiguous pixels disturbed by fire.

The FIREPAT model uses a three-step stochastic strategy implemented at the regional, PVT and succession class level to simulate the start of a fire and its resulting size. The probability of fire starting in any pixel (p_f) is computed using the hazard function of the following three-parameter Weibull probability function (Johnson 1992, Johnson and Gutsell 1994).

$$p_f=(\frac{\beta}{FRI})(\frac{YSB-REBURN}{FRI})^{(\beta-1)}(e^{[-(\frac{YSB-REBURN}{FRI})^{(\beta)}]})$$

The hazard function $Y(p_f)$ is defined as follows:

$$Y(p_f)=(\frac{\beta}{FRI})[\frac{YSB-REBURN}{FRI}]^{(\beta-1)}$$

Where YSB is the years since last burn, FRI is the fire return interval (years), REBURN is the minimum number of years before another fire can occur (years), and β is the shape constant (2.0 used for this study). Probability of fire occurrence increases as the time since disturbance increases depending on the vegetation type (Figure 3). FRI was parameterized mainly at the PVT level with values repeated for all succession classes within the PVT unless other data were available. Parameter defaults were used for those PVT's where fire history or size data were unavailable, which was approximately 30 percent of PVT-region combinations (Table 1).

A uniformly distributed random number is compared to the computed $Y(p_f)$ to determine if a fire has started for the pixel in question. If a fire is simulated, another probability function determines the size of the fire. We used the following function to compute fire size (FIRESIZE in ha).

$$FIRESIZE = \theta[-\ln(p)]^{\beta}$$

Where θ is approximated by the average fire size (ha), β is the shape factor (3.0 used for this study), and p is a number (0-1) generated from a uniform random number generator. Average fire size parameters (θ) were stratified by lifeform group and geographic region (Table 1) to more accurately represent fire dynamics across the ICRB (Figure 4).

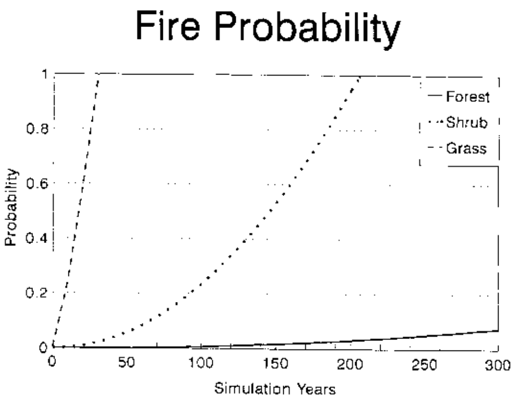

Figure 3. Relationship of years since last burn to the probability of fire occurrence using the default values presented in Table 1.

The synchrony of fires during dry years is also indirectly represented within the FIREPAT structure using a simple stochastic algorithm. Fire sizes are increased by a user-specified factor (2.0 for this study) if a dry fire year was simulated, decreased by a proportion (0.5 for this study) if a wet year was chosen, or remained unchanged if neither a wet nor dry year were selected. The probabilities of a dry and wet year are specified by the user for each geographic region.

TABLE 1. Default input parameters used by the FIREPAT and CRBSUM2 models to simulate fire frequency and size. These defaults were used when no fire interval was available from Keane et al. (1996) and Morgan et al. (1996).

Lifeform biome	Default fire interval (yrs)	Ave fire size (ha)	Years before reburn (yrs)	Shape factor
Forest	150	200	10	3
Shrublands	50	150	2	3
Grasslands	10	100	1	3

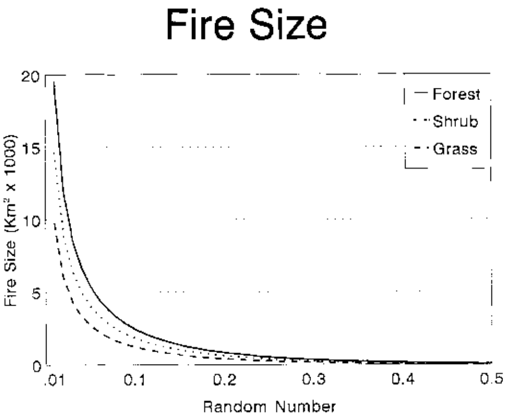

Figure 4. FIREPAT fire size probability relationships for three biome types using default values in Table 1.

The computed fire size defines the dimensions of an truncated paraboloid that delineates the fire perimeter from the following relationship.

$$FIRESIZE = \frac{2}{3} ld$$

Where l is the length and d is the width of the paraboloid in meters. The elongation of the paraboloid (e) or its ratio of length to width is computed from the following Rothermal (1991) equation:

$$e = 1.0 + \left[\frac{0.125(WIND)}{0.44}\right]$$

where WIND is average wind speed (m sec^{-1}) entered by the user. High winds cause long, thin paraboloids. The truncated parabola is then draped over the landscape due east from the pixel where the fire originally started in a "cookie cutter" fashion. All pixels within the paraboloid boundary are considered burned by the fire. Only fires that burn over half the pixel (0.5 km^2 for this study) are actually modeled. Again, as with CRBSUM2, three types of fires (surface, mixed, and stand-replacement) can be simulated for each pixel inside paraboloid boundaries, and the probability of the pixel experiencing a fire type is also defined by the user by successional class. The resultant disturbance pathway for each succession class by fire type determines the simulated fire's subsequent effect on the pixel's cover type, structural stage, and succession age. Unburnable pixels within the fire boundary such as rocklands or lakes do not have fire type probabilities so no disturbance is simulated. Other fire shapes, such as a circles or squares, can be used instead of paraboloids depending on successional class and PVT. FIREPAT was also designed so additional large scale disturbances, such as mountain pine beetle epidemics and harvesting, can be simulated at the same time as fire.

Simulation Specifics

The Interior Columbia River Basin (ICRB) was used as a test area for this simulation comparison (Figure 1). This expansive 82 million ha landscape is very diverse in terms of vegetation, climate, topography, and ownership (Quigley and Arbelbide 1997). ICRB vegetation is described from 127 cover types and 22 structural stages on 55 forest, range, and riparian PVTs (Keane et al. 1996a, Quigley et al. 1996) ranging from dry desert to lush cedar-hemlock forest. Approximately 38 percent of the land in the ICRB is privately owned while 54 percent is public lands with 53 percent in National Forests and Bureau of Land Management lands (Quigley and Arbelbide 1997). Elevations range from 200 meters along the Columbia River to over 3,500 meters along the tallest mountains.

Fire and succession dynamics were simulated on the ICRB landscape for 100 years using an annual time step for all three models. Succession pathway parameters for each PVT were taken directly from the CRBSUM modeling effort for the ICBEMP scientific assessment (Keane et al. 1996a). These parameters were quantified by basin resource specialists from the research literature and from a series of seven workshops held throughout the Basin. All models used historical (circa 1900) cover type, structural stage and potential vegetation type raster maps as initial conditions and historical fire occurrence data to quantify model disturbance parameters (Keane et al. 1996a). Maps of predicted fire occurrence, cover types and structural stages were generated to compare model results and behavior. Annual tabular summaries of predicted succession class and fire occurrence statistics by region and PVT were written to ASCII files for input to statistical programs and databases for subsequent summary and comparison.

Fire probabilities for the CRBSUM simulation were taken from the historical management scenario simulated for the ICBEMP scientific assessment (Keane et al. 1996a). These probabilities were estimated from a variety of empirical fire history research studies including Arno et al.

(1993), Barrett (1988), Barrett (1997), Barrett et al. (1991), Bradley et al. (1992), Crane and Fischer (1986), Davis (1981), Fischer and Clayton (1983), Fischer and Bradley (1987), Heyerdahl et al. (1994), Marsden (1985), Veblen et al. (1993). The ICRB fire regimes map of Morgan et al. (1996) was also used extensively to predict fire intervals for PVT's and cover types where fire history research was rare. CRBSUM2 and FIREPAT fire occurrence parameters were computed directly from the CRBSUM historical fire probabilities. FIREPAT fire size and shape parameters by PVT and succession class were taken mostly from the ICBEMP fire occurrence data layer developed by R. Hartford and L. Bradshaw of the Intermountain Fire Sciences Laboratory, and from the literature, including Barrett (1997), Baker (1989), Johnson (1992), Johnson and Gutsell (1994), Johnson and Van Wagner (1985), Strauss et al. (1992), and Van Wagner (1978). Care was taken to ensure fire probabilities were consistent across model input files so that results could be comparable. For example, FIREPAT would generate results similar to CRBSUM if fire size was set at 1 km^2 because fire occurrence probabilities were identical.

Results and Discussion

Model Behavior

FIREPAT burned nearly eight times the amount of land compared with CRBSUM and CRBSUM2 (Figure 5). The year-to-year variation (i.e., white noise) of FIREPAT predictions was surprisingly low (approximately 2-3 percent), and this variation seemed to increase as the amount of burned area reached an asymptote towards the end of the 100-year run (Figure 5). Although burned area for the minimum year compares well across all models (Table 2), FIREPAT's simulation of over 15 percent of the ICRB burning by year 100 seems high, but it is below the maximum area calculated from Morgan et al.'s (1996) fire regimes map (Table 2). It is probably unrealistic to think that nearly a sixth of the ICRB burned every year. The high FIREPAT burn estimates is most likely the result of inaccurate fire size parameterizations for many PVT-cover type combinations and an incompatibility with high fire frequency probabilities. We expect the adjustment of these parameters as new data become available will ultimately produce more realistic results and patterns.

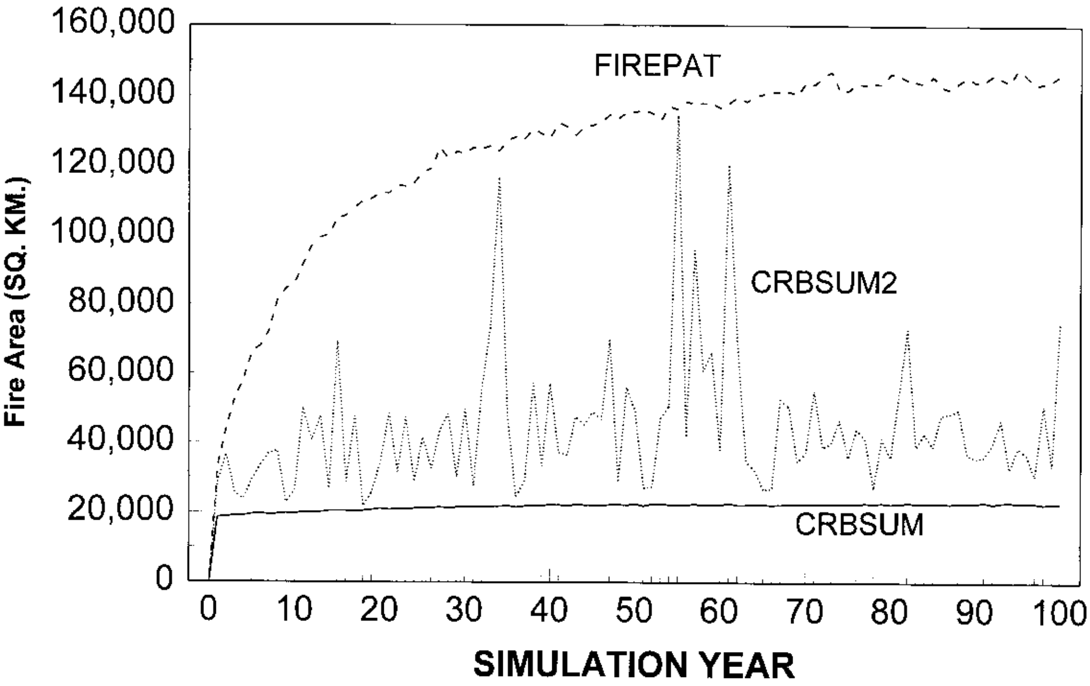

Figure 5. Area burned by fire over the 100 years of simulation as predicted from the three models CRBSUM, CRBSUM2, and FIREPAT.

TABLE 2. Predicted area burned by fire and patch dynamics (1,000 km^2) over the 100 years of simulation for the three coarse scale vegetation dynamics models. Number in parentheses represents percent of simulation area which is about 821,000 km^2. Estimations of area burned calculated from the Morgan et al. (1996) fire regime map is included for reference.

Landscape attribute	CRBSUM	CRBSUM2	FIREPAT	Fire regime map
Fire Area				
Minimum	18.5 (2)	21.8 (3)	32.8 (4)	13.1 (2)
Maximum	23.1 (3)	134.4 (16)	148.9 (18)	199.3 (24)
Ave. annual	21.8 (3)	44.4 (5)	125.7 (15)	22.5 (3)
Patch Statistics				
Ave. size	1.5	2.6	13.5	—
Minimum	1.0	1.0	1.0	—
Maximum	26.0	2056.0	1042.0	—
Number Patches	2522	2524	680	—

Simulated fires in CRBSUM and CRBSUM2 burned about the same amounts of average annual area as computed from the Morgan et al. (1996) fire regime map (Table 2). CRBSUM burned nearly constant amounts of area each year with less than 2 percent year-to-year variation (Figure 5) and the average annual burned area very close to Morgan et al. (1996) average estimates (Table 2). CRBSUM2 simulations generated highly variable year-to-year predictions (Figure 5) that compare well with anecdotal evidence of the variation in historical ICRB fire years (Barrett 1997), but the amount of burned area was much higher than that computed from Morgan et al. (1996) (Table 2). The larger area burned by CRBSUM2 is probably a result of the fire frequency probabilities not being adjusted for the size of region-PVT patches and inaccurate PVT delineations.

The highest temporal variability of coarse scale fire is simulated by CRBSUM2 with a range of 120,000 km^2 for the 100 year simulation (Figure 5). Predicted year-to-year variation in area burned is lowest in the CRBSUM (range of 2 percent of average), while FIREPAT had a range of only 15,000 km^2 once the upward trend was removed. The synchrony of fire years was not well represented in any of the models, but CRBSUM2 seems to simulate fire synchrony best, even though it was not explicitly modeled. We think FIREPAT could better model fire synchrony if some equation parameters were modified using trial-and-error iterative techniques, and if fire parameters were stratified by finer divisions of geographic region and PVT. The dry and wet year FIREPAT simulations worked to an extent but these stochastic parameters need adjustment. It is apparent from the high predictions of fire area that CRBSUM2 and FIREPAT fire occurrence parameters need to be adjusted to account for the spatial and temporal scaling of fire frequency probabilities inherent in both models (Figure 5).

The spatial pattern of fire on the ICRB landscape was best represented by FIREPAT simulations (Figure 6). The small patches generated by CRBSUM were almost always the same size (1 km^2) (Table 2) and tended to be randomly distributed across time and space (Figure 6a). This produced a salt and pepper or uniform spatial distribution of fire-disturbed pixels, whereas fire patches explicitly generated from CRBSUM2 tended to be large and diversely shaped (Table 2, Figure 6b). Moreover, CRBSUM2 patches were always confined to PVT-region boundaries which resulted in the burning of the same patch shape and size whenever a fire was stochastically simulated for that PVT-region combination, because both PVT and geographic region boundaries were static on the ICRB landscape. CRBSUM2 assumes topography is the main influence on fire size and shape because PVT-region boundaries were created from topographical constraints (Reid et al. 1996). However, Bessie and Johnson (1995) note that weather, primarily wind and drought, are major determinants of large scale fires in subalpine forests, while fuels and topography play minor roles.

FIREPAT fire patches seemed more realistic because they consistently crossed PVT and region boundaries and were shaped somewhat like

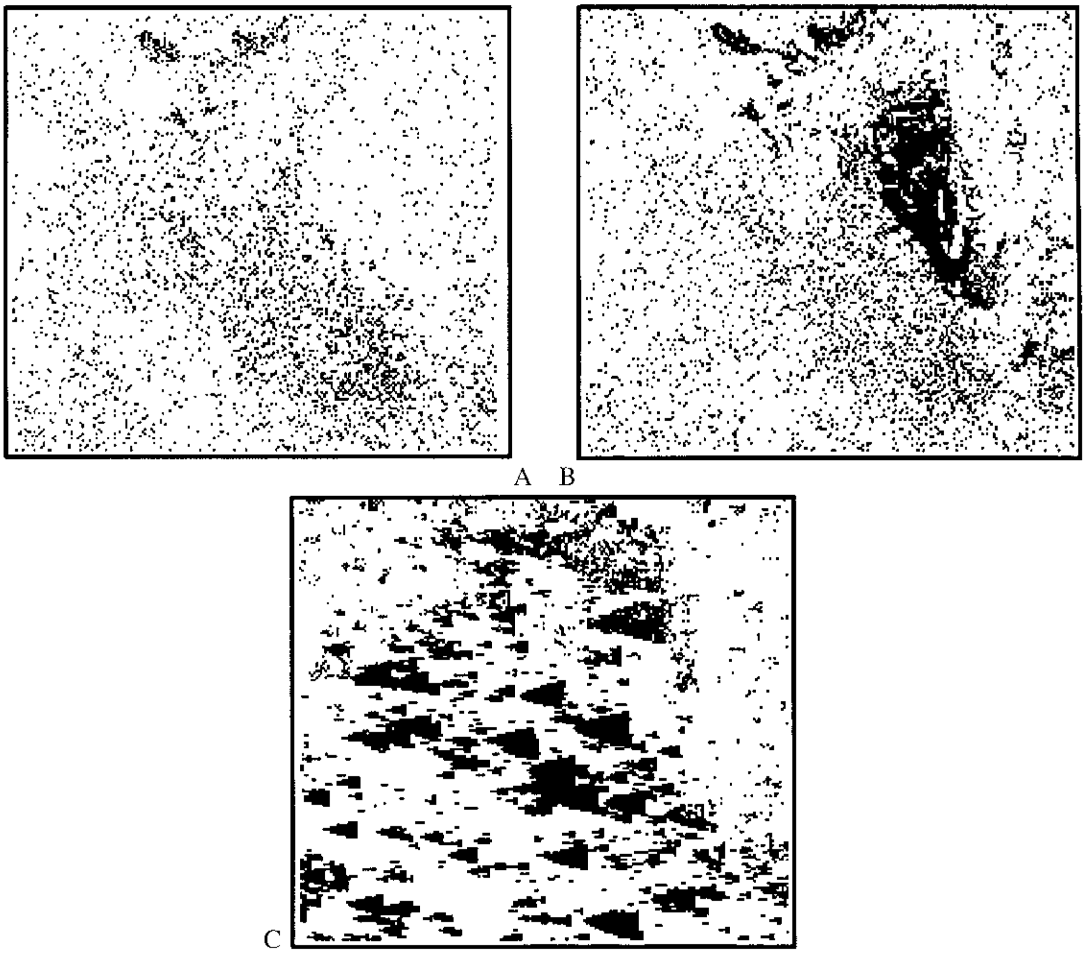

Figure 6. Patches of burned pixels as predicted from the three models after 10 years of simulation for a portion of the ICRB simulation area (see Figure 1). a) uniformly distributed CRBSUM pixels. b) static CRBSUM2 patches. c) truncated paraboloid FIREPAT patches.

large fire perimeters (Figure 6c). Also, FIREPAT seems to best represent realistic distributions of fire shapes because of the wide distribution of sizes (Table 2) (Barrett et al. 1997). However, the constant paraboloid shape always spreading eastward did not match some observed spatial fire distributions (Barrett et al. 1997). Large fires often follow topography and wind pattern shifts and this was not explicitly simulated in FIREPAT. The truncated paraboloid shape assumes the large scale fire was driven only by wind coming from the west. So CRBSUM2 indirectly simulates topographical effects while FIREPAT only simulates constant wind effects on fire pattern. An integration of the two approaches without sacrificing simplicity may prove a better modeling approach.

Predictions of ICRB landscape composition at year 100 were quite different for important cover types across the three models (Table 3). The large amount of fire simulated by FIREPAT generally maintained fire-dependent cover types and caused a larger portion of the ICRB landscape to be in early seral structural stages. Statistics computed from Losensky's (1994) historical cover type map are included in Table 3 for reference because many believe that the vegetation as it appeared circa 1900 may be in dynamic equilibrium with disturbance, and therefore, the ICRB landscape at the end of a 100 year run should be similar to the Losensky (1994) map. However, only FIREPAT seems to generate the fire needed to maintain the extent of some historical vegetation types as predicted by Losensky (1994) (Table 3) except for the sagebrush and grassland cover types which comprise over 40 percent of the ICRB. Fires convert sagebrush to grassland and the high levels of fire in FIREPAT and CRBSUM2 created landscapes that have twice the amount of grassland compared to sagebrush which is exactly opposite from Losensky's (1994) predictions. Moreover, the large range of sagebrush and grassland coverage over the 100 years of simulation indicates a landscape that is not in dynamic equilibrium (Table 3). More historical information is needed to investigate the accuracy of these simulation results. CRBSUM predicted an increase in ponderosa pine cover type over the 100 years of simulation, whereas FIREPAT simulations show a somewhat constant level of ponderosa pine and CRBSUM2 predicts a decline in ponderosa pine (Figure 7). This is probably because the high CRBSUM2 fire levels, where entire region-PVT patches are burned, does not allow any area to escape the fire and fires occur so frequently that some areas are unable to become dominated by ponderosa pine cover type, especially in the Douglas-fir PVT.

Fire severity types compare well across the three model simulations because quantification of fire type probabilities were from CRBSUM input files and fire effects were modeled at the pixel level (Table 4). However, the FIREPAT prediction of nearly 80 percent of all fires as stand-replacement fires for the entire ICRB seems too high (Barrett et al. 1997). The majority of FIREPAT stand-replacement fires occurred in the sagebrush cover types, but a number of fires started in PVT's with frequent fire regimes became large enough to burn into montane PVT's where stand-replacement fire regimes are common. Interestingly, FIREPAT appears to simulate more non-lethal underburns in dry forested lands than the other models, especially in the ponderosa pine PVT (Table 4) yet the model does not predict more ponderosa pine by year 100 (Table 3). This is again because of the great amounts of fire simulated by FIREPAT did not allow successional change to a cover type that can experience a mixed or stand-replacement fire, and PVT's where ponderosa pine is seral did not experience the type of fire to maintain that species. The random distribution of CRBSUM-generated fires tend to create a more homogeneous landscape with low temporal and spatial variability in fire pattern and severity (Table 4).

CRBSUM appears to best predict the distribution of forest structural stages with reference to the historical structure of pre-1900 forests compiled by Losensky (1994) (Table 5) but does not predict realistic structural stage patches. The high fire levels predicted by FIREPAT do not create the historical forest stand structure estimated by Losensky (1994). It seems many FIREPAT fires do not burn enough old growth multi-strata stands to create the many mid-seral, stem exclusion stands found around the turn of the century (Table 5). Also, CRBSUM2 fires do not seem to create many stem exclusion stands probably because the PVT's that contain these stages do not burn enough to match historical conditions.

Model Comparison and Limitations

Results from this study demonstrate the difficulty of balancing model utility with reality of predictions when spatially simulating coarse scale fire effects. Simplistic models such as CRBSUM, which are easy to parameterize and execute, often produce homogenized results without realistic temporal variability and spatial pattern (Table

TABLE 3. Predicted average annual coverage of five important cover types expressed as percent of the total simulation area for the three models. Numbers in parentheses are the range of cover type extents in percent of entire ICRB over the 100 years of simulation. Historical cover type map composition (Losensky 1994) is included for reference.

Cover type	CRBSUM	CRBSUM2	FIREPAT	Historical cover type map
Ponderosa pine	13.1 (1.1)	11.0 (1.8)	9.8 (0.5)	11.9 (—)
Douglas-fir	8.5 (2.4)	7.3 (1.8)	8.1 (2.0)	6.0 (—)
Subalpine fir	2.9 (0.8)	1.3 (2.3)	3.0 (0.8)	3.7 (—)
Sagebrush	24.3 (8.1)	14.9 (22.0)	15.5 (16.3)	32.6 (—)
Grassland	20.5 (6.3)	32.7 (21.1)	30.2 (15.0)	15.0 (—)

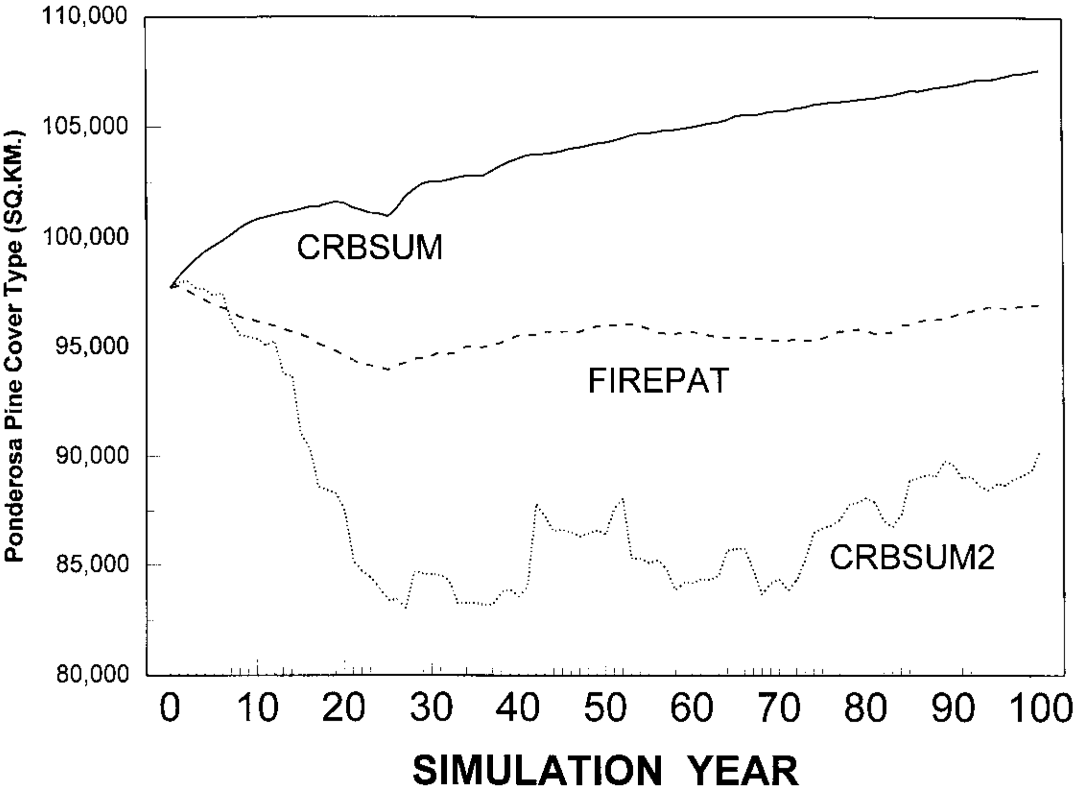

Figure 7. Extent of ponderosa pine cover type (km^2) as predicted by the three models over the 100 years of simulation.

TABLE 4. Average annual amount of land (1,000 km^2) burned by fire severity type as simulated from the three models over 100 years of simulation. Numbers in parentheses are the percent of simulation landscape that was burned.

Fire severity	CRBSUM	CRBSUM2	FIREPAT
Entire ICRB			
Stand-replacement	11.5 (53)	25.4 (57)	99.0 (79)
Mixed fire regime	3.0 (14)	5.8 (13)	8.8 (7)
Non-lethal underburn	7.3 (33)	13.2 (30)	17.8 (14)
Ponderosa pine PVT			
Stand-replacement	0.3 (14)	0.5 (11)	0.3 (6)
Mixed fire regime	0.8 (30)	1.1 (26)	0.6 (16)
Non-lethal underburn	1.4 (56)	2.6 (63)	3.2 (78)

2, Figure 5). More complex models such as CRBSUM2 and FIREPAT produce better temporal and spatial fire distributions (Figure 6), but it is difficult to quantify their copious input parameters, and their outputs may be more difficult to interpret. For instance, the multiple scale simulation architecture used in FIREPAT requires nearly five times the parameters needed by CRBSUM, and the model takes much longer to execute and produces more output (Table 6).

Complex models generally require more computer resources and additional time for parameterization, but also tend to produce more realistic results (Table 6). This is especially important when one considers the potential uses of such models. Management applications of these models may require many computer runs to compare the impacts of alternative land management strategies, so setup and execution time are important factors to consider when rating model utility (Table 6). Over 50 simulations of CRBSUM, each averaging 50 hours of execution time, were needed by Keane et al. (1996a) to simulate various management scenarios for the ICBEMP effort. Conversely, research may only need a few executions of a model to investigate some ecosystem characteristic, so realistic results may be more important than parameterization and execution costs. In short, model design should match simulation

TABLE 5. Average annual amount of land (1,000 km^2) in the forest structural stages across the ICRB at the end of the 100 years of simulation. Numbers in parentheses are the percent of simulation landscape that is forested. Historical structural stages are from Losensky (1994).

Forest structural stage	CRBSUM	CRBSUM2	FIREPAT	Historical map
Stand initiation	58.8 (16)	72.7 (19)	59.9 (16)	58.0 (15)
Stem exclusion	84.1 (22)	67.5 (18)	74.4 (20)	103.5 (27)
Stand reinitiation	46.3 (12)	35.4 (9)	44.0 (12)	27.5 (7)
Old growth multistrata	71.3 (19)	54.1 (14)	77.7 (21)	57.6 (15)
Old growth single strata	56.2 (15)	57.7 (15)	41.4 (11)	49.8 (13)
Young multistrata	7.4 (2)	6.6 (2)	6.1 (2)	16.4 (4)

TABLE 6. Comparison of simulation characteristics across the three models used in this study for a 100 year simulation run. Parameters are disturbance parameters only, the same number of succession parameters are present for all three models.

Comparison items	CRBSUM	CRBSUM2	FIREPAT
Complexity	Low	Moderate	High
Region-level parameters	0	0	6
PVT-level parameters	0	337	0
Succession class-level parameters	7,000	7,000	35,000
Preparation time[1]	1.0	1.5	3.0
Execution time (hrs)[2]	24	25	36
Interpretation difficulty	Low	Moderate	Moderate
Spatial pattern realism	Low	Low	Moderate

[1] Preparation time is relative to time spent to prepare the CRBSUM model

[2] Executed on IBM C10 UNIX workstation

objectives. If fire patch dynamics and spatial patterns are important for the model application, then FIREPAT or a percolation model may be appropriate, but only if ample computer resources, parameterization time and expertise are available. On the other hand, if relative trends of generalized model output will satisfy modeling objectives, then perhaps CRBSUM or CRBSUM2 may be more appropriate.

It was extremely difficult to rectify fire size, fire occurrence, and fire effects parameters to generate accurate simulation results. CRBSUM produced realistic yearly fire estimates (Table 3) because only one set of parameters was used to calculate fire dynamics and these were computed from sources similar to those used for the fire regimes maps (Morgan et al. 1996). However, scale and statistical problems arise when fire size and synchrony are explicitly simulated with CRBSUM fire occurrence data as in the CRBSUM2 and FIREPAT models. Fire frequency parameters must be adjusted to agree with the fire size and timing parameters to make FIREPAT and CRBSUM2 results more accurate. This is difficult to accomplish using information from the literature because most studies did not quantify fire dynamics at coarse scales and they did not extensively map fire perimeters. It seems the only short-term option available to make simulated fire statistics more realistic is to adjust fire size and fire frequency parameters to achieve believable results.

Quantification of fire input parameters for all three models was incomplete and limited in this comparison effort. Fire probabilities in CRBSUM input files were estimated by fire specialists and natural resource personnel from the literature and personal experience (Keane et al. 1996a). Most fire occurrence probabilities needed by CRBSUM2 and FIREPAT were estimated from the CRBSUM input files used for the ICBEMP effort. Often, we did not have time to verify that estimated parameters produced desired levels of disturbance in the model. Fire size and shape parameter coefficients for FIREPAT were roughly estimated from a 6-year fire occurrence database created for the ICBEMP and also from the literature and fire records. Unfortunately, many ecosystems and geographic areas did not have adequate data to accurately quantify most fire occurrence and size parameters so we assigned parameters based on the most similar biophysical setting (Table 1). Some FIREPAT fire size parameters were adjusted to produce more realistic fire dynamics, but overall, nearly all fire parameters were computed to be in agreement across all three model runs. For example, the probabilities of fire occurrence in a sagebrush grassland were identical across all three model input files. What is needed is a dynamic algorithm that mechanistically computes fire parameters (size, frequency, severity) from a quantification of the biophysical setting (e.g., rainfall, soils, evapotranspiration, vegetation). This way the fire regime can vary as the vegetation and climate change.

This model comparison is by no means comprehensive and complete. Many other modeling strategies could have been included in this effort to account for the full range of coarse scale fire effects modeling strategies. However, we could not do this because of time and computer resource limitations, and also we assumed that most other strategies are more complex than FIREPAT and models of this high complexity would be less useful to land management. Cell automata and percolation models are definitely useful in coarse scale fire pattern simulation and they probably will produce more realistic fire patterns than FIREPAT, but they can require many input parameters and computer resources, and their results might be difficult for land managers to interpret. In addition, they still must have a fire ignition routine that realistically starts fires across the landscape based on site, climate, and vegetation, and this requires still more input parameters. We are currently developing a simplistic coarse scale fire percolation model based on FIREPAT structure.

Probably the most complex simulation approaches are coarse scale applications of process-based fire growth models such as FARSITE (Finney 1994) and SiroFire (Coleman and Sullivan 1996). These models may eventually produce the most realistic representations of fire patterns and severities, but their application to coarse scale landscapes is problematic, because the fundamental physical relationships used by the models require fine scale input data. Even if the cross scale incompatibilities were remedied, these models would be difficult to use for land management because they require accurate, spatially-explicit representations of climate, fuels, vegetation, and topography to predict fire growth, and these layers are difficult to create and maintain at a coarse scale. Moreover, most process-based models are again missing a comprehensive fire start component. Perhaps future coarse scale fire simulation approaches will be an extrapolation of fine scale results from process-based models into coarse scale fire pattern and fire effects models. For example, the FARSITE model would be exercised on a large, high-resolution landscape to estimate the distributions of fire sizes and shapes, and those distributions could be employed in a coarse scale fire model.

Conclusions

Selection of a coarse scale fire effects modeling strategy depends on the objective of the simulation effort. Realism and accuracy must be balanced with computing power, parameterization time, and model complexity to choose an appropriate modeling approach (see Table 6). Computing resources, parameterization difficulty, and output intricacy usually increase as model complexity increases, but so do accuracy and realism. Mechanistic approaches to coarse fire modeling must rectify coarse scale data with fine scale input requirements before they will be useful for land management. Ultimately, the user must decide which modeling approach best suits the model application. Lastly, no model will consistently produce accurate results, so it is important that users compare predicted trends rather than absolute numbers.

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