Applying Fire Spread Simulators in New Zealand and Australia: Results from an International Seminar

Tonja Opperman[1], Jim Gould[2], Mark Finney[3], and Cordy Tymstra[4]

Abstract—*There is currently no spatial wildfire spread and growth simulation model used commonly across New Zealand or Australia. Fire management decision-making would be enhanced through the use of spatial fire simulators. Various groups from around the world met in January 2006 to evaluate the applicability of different spatial fire spread applications for common use in both New Zealand and Australia. Developers and researchers from Canada, the United States, and Australia were invited to apply Prometheus, FARSITE, and other similar models to New Zealand and Australian wildfires in grass, scrub, and forested fuel types. Although the lack of site-specific fuel models and weather data were a concern, coarse spatial and temporal data inputs proved adequate for modeling fires within a reasonable margin of error. The choice of grass models proved less important than expected since spread rates were easily manipulated through moisture content values during calibration. The final modeled perimeters are affected by several user inputs that are impossible to separate from model error. These various inputs exist to allow experienced users to approximate local environmental variability as closely as possible to obtain successful outputs. Rather than attempt to quantify direct comparisons, local users concluded it was more important to choose an application that provides an appropriate level of functionality, that is compatible with current data and fire management systems, and that can be easily modified to use unique and varied fire spread equations. Prometheus and FARSITE performed very well and will be further investigated to understand how each might be customized for use with local fire spread models. This paper describes the process and results of testing some existing fire growth simulation models for use on fires in New Zealand and Australia.*

Introduction

Australian and New Zealand fire managers have a need for spatial fire spread simulators for planning and operations. The New Zealand Department of Conservation (DOC) and the National Rural Fire Authority are interested in adopting a spatial fire growth simulation model for enhanced decision-making. New Zealand's native vegetation is not generally fire-adapted, and DOC must measure conservation success by comparing the actual area burned to the potential area burned without suppression. Australia, a more fire-prone nation, has experienced some of its most devastating wildfires in the past two decades with significant damage to property, infrastructure, and the environment, including loss of civilian lives. In response to these wildfires, the Australian government has recommended continued development and

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[1] Fire Ecologist, U.S. Department of Agriculture, Forest Service, Bitterroot National Forest, Hamilton, MT U.S.A. and Wildland Fire Scientist, Ensis Bushfire Research, Christchurch, New Zealand. tsopperman@fs.fed.us

[2] Research Leader, Ensis Bushfire Research, Christchurch, New Zealand and Research Leader, Ensis Bushfire Research, and Bushfire CRC Program Leader, Kingston, ACT, Australia 2004.

[3] Research Forester, U.S. Department of Agriculture, Forest Service, Fire Sciences Laboratory, Missoula, MT U.S.A.

[4] Fire Science and Research Officer, Wildfire Policy and Business Planning Forest Protection Division, Alberta Sustainable Resource Development, Edmonton, Alberta, Canada.

coordination of wildfire simulation models to enhance decision-making. Unlike New Zealand, Australian land management agencies need to conduct prescribed burning for hazardous fuel reduction. Using a simulator to assess changes in risk over time and space would be helpful. Additionally, private plantation companies in both nations are interested in how various wildfire scenarios might affect their investments. Fire researchers are investigating whether a current model can be adapted for use in Australasia, or whether a new simulator requires development.

In recent years, with advances in computer speed and modeling, storage capacity and graphical capabilities, some fire behavior models have been implemented in spatial fire growth simulation models. These models can aid in understanding strategic placement of fuel treatments on the landscape to reduce overall fire spread and potential fire behavior (Finney 2002; Vojtek 2006). A spatial fire simulation tool allows fire managers to quickly simulate several potential fire scenarios and helps them evaluate fire effects at a landscape scale.

Wildland fire simulators combine spatial and temporal representations of fuels, weather, and topography to propagate point, line or polygon ignitions. Fire simulators are not new fire behavior models. Calculations depend on the underlying mathematical expressions representing what are commonly referred to as 'fire behavior models'. Familiar surface fire spread models include empirical models developed by McArthur (1967) and Forestry Canada Fire Danger Group (1992), and the semi-empirical model developed by Rothermel (1972). Some simulators incorporate additional models to calculate spotting and crown fire initiation (Pastor and others 2003). Worldwide, over twenty spatial wildland fire simulators have been developed for operations, planning, and research (Pastor and others 2003). Most of these simulators are designed to handle specific areas and requirements; few are sufficiently robust for trans-continental applications (Johnston and others 2005). Ensis Bushfire Research hosted an international workshop to evaluate several spatial fire spread simulators that could be adopted in New Zealand or Australia. This paper describes the process and results of testing some existing fire growth simulators for that purpose.

Fire Environments

The fire environments and fire histories of New Zealand and Australia are markedly different.

New Zealand consists of two main islands of 270,000 square kilometers isolated in the southwest Pacific Ocean. Indigenous vegetation types are not generally considered fire adapted and New Zealand experiences relatively few naturally ignited fires. Pine plantations, pasture grasslands, and exotic shrubs comprise the majority of non-native vegetation types that burn readily from human-caused ignitions. Rapidly changing conditions dominate the maritime-influenced weather and unrelenting winds exceeding 80 km/h are common. New Zealand has approximately 2500 rural vegetation fires each year that, combined, burn approximately 7000 hectares. Fires are considered "large" if they are greater than 50 hectares and spread for more than one burn period.

Australia is located between the Indian and Pacific Oceans and is 7 million square kilometers, thus supporting a continental climate. Bushfires are an inherent part of the Australian landscape. Few areas of Australia are free from fire, and every decade, intense and widespread fires burn in southeast Australia. As an example, the spring of 1974 witnessed 15% of Australia's land area burned (Luke and McArthur 1978), and from 1960-2001 there were 224 fire-related deaths, over 4500 injuries, and $2475 million dollars in damages (McMichael and others 2003). As such, this area has a reputation as one of the three most fire-prone areas in the world along with southern California and southern France. Although fire has proven important to the local ecosystems by shaping vegetation mosaics and maintaining biodiversity, it is one of the most significant threats to human populations and infrastructure. Throughout the 20th century, many fires have claimed lives, destroyed homes and livelihoods, and burned thousands of hectares. Land managers and fire management agencies reduce this risk through a range of measures before and during fires.

Fire Spread Models and the Need for a Common Simulator

New Zealand and Australia have approached fire spread modeling somewhat differently. New Zealand fire managers have adapted a limited number of empirical fire spread models, mostly from the Canadian Fire Behavior Prediction system (FBP, Forestry Canada Fire Danger Group 1992; Pearce and Anderson 2004; Opperman and Pearce 2005). Australian researchers have developed empirical models based on experimental burns supplemented by reliable wildfire observations. Both nations use qualified fire behavior analysts to predict fire spread and behavior using computational spreadsheets or calculators and paper maps on fire incidents. The McArthur Forest Fire Danger Meter (McArthur 1967) and Western Australia Forest Fire Behavior Tables (Sneeuwjagt and Peet 1985) are commonly used for fire behavior prediction in open eucalypt forests in Australia, while Pearce and Anderson's guide (2004) is used in New Zealand. Although fire behavior analysts can readily provide point-based calculations and a perimeter for a single weather scenario, this time-intensive process leaves little time to develop potential perimeters for a variety of possible weather scenarios. Often, the Incident Commander has no basis for judging the error associated with the supplied perimeter. In contrast, fire behavior analysts in the United States and Canada have spatial fire simulators in their suite of predictive tools to quickly develop several potential fire perimeters based on different weather scenarios.

Australia and New Zealand would benefit from adopting the same fire spread simulator. Although each nation can see immediate benefits by adopting the simulator that most closely reflects current fire management systems, this may prove difficult to manage in the long term. Fire management organizations in both nations are experiencing a shortage of firefighting personnel and a loss of the technical skill base. Therefore, operational resources are often shared. If one simulator could be used in both countries, the resulting common technology transfer would represent a cost savings and allow skilled fire behavior analysts to be shared. Although New Zealand and Australia differ in regards to fire history, fuels, and fire behavior models, both have a private and public need for fire simulation models.

Simulators Evaluated at the Workshop

Six fire simulators were presented at the workshop. Five of these simulators are systems that combine different fire behavior models with multi-dimensional mathematical models to predict rates of spread in complex environmental conditions varying spatially and temporally. Time-dependent fire spread is calculated appropriate to local conditions to output tabular or graphical representations of fire area, fire perimeter, fire numbers, and fire characteristics. Of the simulators examined at the seminar, FARSITE (Finney 1998) and Prometheus (Tymstra and others 2006) are operational in their respective countries; the Portable Fire Growth Model (Shamir, pers. comm.) and the Bushfire CRC computer simulation project are under development (Johnston, pers. comm.). Networked Fire Chief (Omodei and others 2004) is not a fire spread simulator, but a research decision tool to generate fire scenarios. A new model based on Minimum Travel Time (MTT, Finney 2002) was also demonstrated. This technique solves for fire arrival time across the landscape using Fermat's principle, which is essentially the inverse of Huygen's and produces nearly identical results given homogeneous temporal data. This evaluation focuses on the two mature operational fire spread systems—FARSITE and Prometheus.

FARSITE (Finney 1998) was developed in the U.S. and has been in use since the early 1990s (Finney 1994). It relies on a wave-front expansion technique called Huygens' principle to achieve two-dimensional elliptical fire growth (Anderson 1983; Richards 1990) using existing one-dimensional models of fire behavior. Fire behavior support in FARSITE includes surface fire (Rothermel 1972), crown fire (Van Wagner 1977, 1993; Rothermel 1991), dead fuel moisture (Nelson 2000) and spotting from torching trees (Albini 1979). FARSITE generates vector and raster maps of fire growth and behavior (time of arrival, fireline intensity, rate of spread, flame length, heat per unit area, and fire type), which can be exported as ASCII grids. FARSITE inputs may be used with FlamMap, which computes fire behavior for every landscape cell using a single wind and weather scenario. FlamMap includes the recently developed and experimental fire simulation techniques called the Treatment Optimization Model (TOM, Finney 2001) and Minimum Travel Time (MTT, Finney 2002).

The Canadian fire growth simulation model, *Prometheus*, was also tested. The foundations of the *Prometheus* model are the Fire Weather Index (FWI) and the Fire Behavior Prediction (FBP) Sub-Systems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1987; Forestry Canada Fire Danger Group 1992). *Prometheus* incorporates two sets of elliptical growth equations to mathematically expand the elliptical wave front: two-dimensional differential equations defined in Richards (1990) and three-dimensional equations defined in Richards (1999) to simulate fire growth over a three-dimensional surface. A variety of FBP outputs (fire intensity, rate of spread, surface fuel consumption, crown fuel consumption, and total fuel consumption) can be exported as ASCII grids. Software engineering of *Prometheus* began in 2000. The Microsoft COM architecture of this model provides for the reusability and extension of its components. As examples, burn probability mapping applications such as Burn-P3 (Parisien and others 2005) and batch routine applications such as Pandora re-use Prometheus functionality.

Methods

Acquiring Simulation Data

Inputs for the fire simulators differed slightly, though each required a digital elevation model (DEM), weather, and fuel data. Although the DEMs were relatively easy to acquire and import into the simulators, it proved difficult to identify wildfires with adequate geospatial records and nearby weather stations or on-site weather observations, fire narratives, or photographs of fire behavior. In New Zealand, all final perimeters are impacted by suppression within the first burning period, which makes it difficult to assess free-burning fire behavior. Conversely, Australia experiences very fast moving, high intensity fires that are difficult to quantify during the event. Weather data, once acquired, had to be manually transformed into unique input files for each application. In some cases, the nearest weather station data were recorded 15 kilometers from the fire and did not reflect conditions at the fire site. Visiting the site, speaking with the Incident Commander, and making insightful adjustments to the wind direction values were necessary to spread the simulated fire in the observed direction.

The required fuel model grids were not readily available. FARSITE requires ASCII grids of Rothermel-based fuel models (Rothermel 1972; Anderson 1982; Scott and Burgan 2005) and canopy cover. Prometheus also requires ASCII grids of FBP fuel models. New Zealand had a local fuel model map derived from the national vegetation database. Australia had fuel maps coded in "grass" and "forest" fuel models. We used a satellite-derived land cover database with vegetation descriptions to assign the required fuel types judged to be reasonably close in fuel depth and loading to those models available for each simulator. Estimates were confirmed through on-site visits and discussions with experienced fire managers, helping to refine fuel maps. Several optional layers can be used in FARSITE for modeling crown fire initiation and spotting firebrands from trees, but the vegetation databases did not contain attributes other than land cover classes. Tree height and crown base height were estimated for each fuel type based on local knowledge; a constant value was used for crown bulk density. Prometheus was designed to use Canadian-based fuel types, and modifications were made to incorporate the custom New Zealand fuel types that are based on the Canadian models. Empirical fire behavior data were available to assist fuel model assignments in some fuel types.

Simulating the Fires

Two New Zealand fires and one Australian fire were modeled during the workshop. Before modelers were asked to predict fire spread, it was necessary to discuss the local fire environments. Invited modelers, Ensis research staff, and local DOC fire managers visited several New Zealand fire sites to discuss local fuels, weather, topography, and burn progression. The Australian fire environment, fire behavior, and fire reconstruction were detailed in a slide presentation (Jim Gould, pers. comm.).

Data were provided to modelers both before and during the workshop. Providing data before the workshop allowed modelers to assess data quality and convert files to formats unique to their applications. New Zealand input data were made available to modelers one month prior to the meeting. These data included tabular fire weather data; shapefiles of fire ignition points and times, final fire perimeters and times; ASCII grids of elevation, aspect, slope, and local vegetation types; and a crosswalk table for creating new ASCII grids of fuel models specific to each application. The final data were provided at the workshop. Australian data were provided at the start of the workshop to test the applications' ability to quickly import data from a new source.

Fire Simulation Results

Participants assembled in one room to concurrently run the simulators on each fire. Input parameters were first discussed to ensure simulators used the most similar and accurate inputs as possible with regard to weather stations, wind speed modifications, use of fire spread barriers, manual fuel type changes, and simulation duration. The group examined the results in detail after each fire was modeled. These results serve to compare not only the applications but also the underlying fire behavior fuel models.

Craigeburn Fire, New Zealand

The Craigeburn Fire was a human-caused point ignition in the Canterbury region of the South Island in January 2004. It burned 548 hectares in tussock grassland with mixed hardwood and native shrub gullies. Full suppression actions with aircraft began within an hour of the ignition. The fire spread for approximately seven hours under strong northerly winds.

Figure 1 illustrates the Craigeburn Fire model results from FARSITE and Prometheus. When the fire was first modeled using the wind stream from the distant weather station, the fires spread east rather than south. Therefore, the teams modified the weather file wind directions, but left the wind

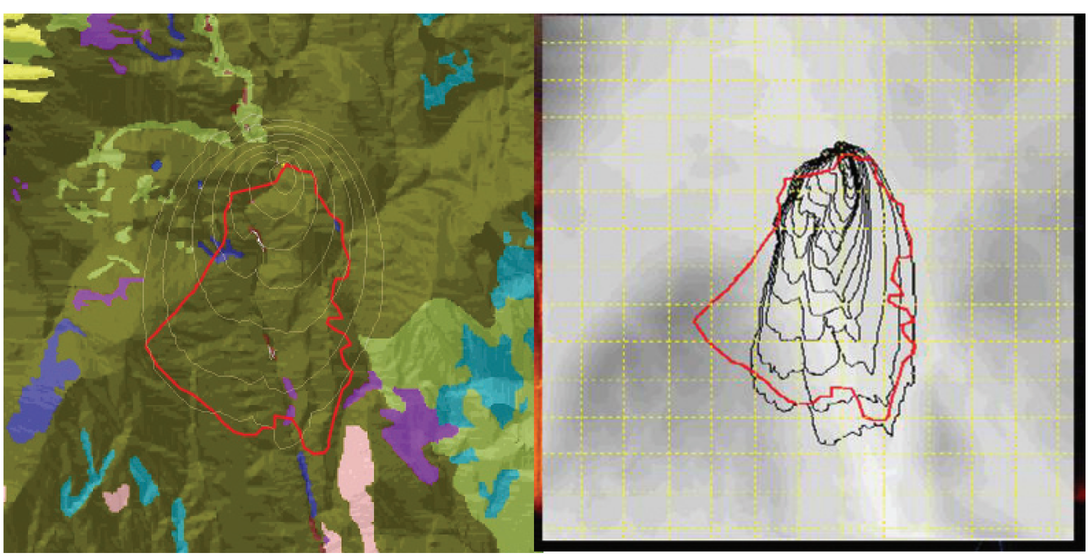

Figure 1—For the New Zealand Craigeburn Fire, FARSITE (left) simulated fire perimeters (white) against the final fire perimeter (black); Prometheus (right) simulated perimeters (black) against the actual fire (red). Both simulations are reasonable, especially if the effect of suppression is considered.

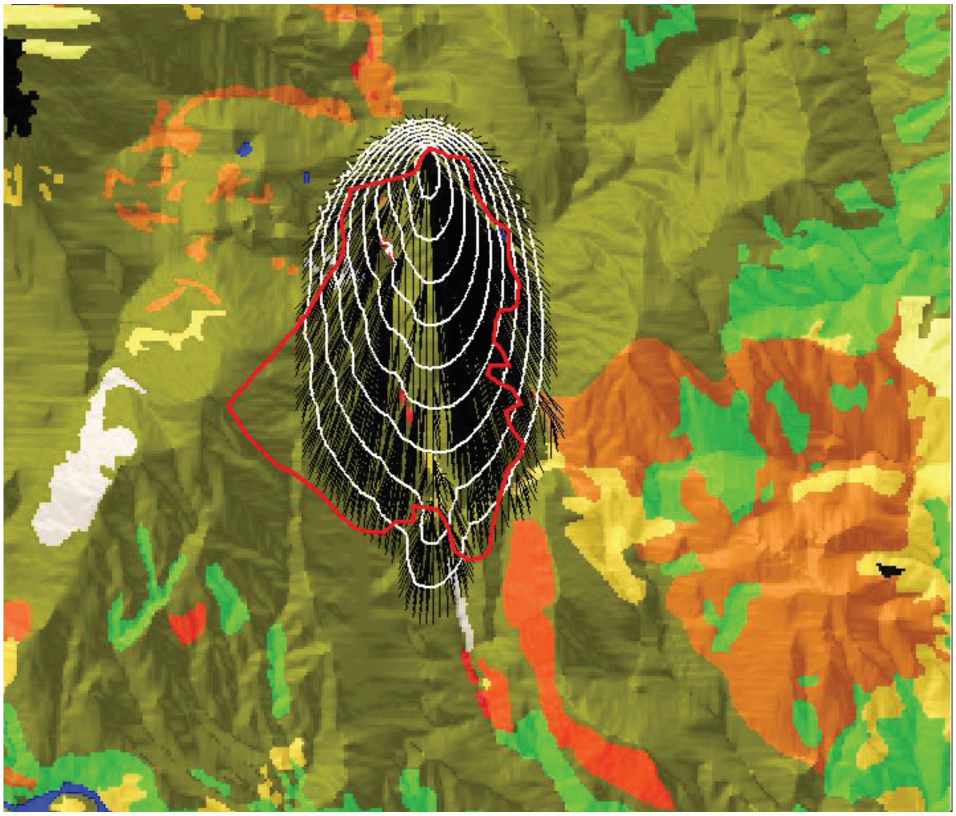

Figure 2—The Minimum Travel Time (MTT) model shows a slightly different shape for the New Zealand Craigeburn Fire. Although it uses the same fire behavior models as FARSITE, it propagates fire through regularly spaced nodes (Fermat's principle) rather than wave fronts (Huygens' principle) and uses constant rather than varied wind and weather inputs.

speed untouched. FARSITE over-predicted the right and left flanks and the extent of the backing fire, while predicting the heading fire well. Prometheus under-predicted the fire's right flank, slightly over-predicted the heading and backing fires, and predicted the left flank well. Considering that suppression dramatically reduced the actual fire extent, both models achieved a reasonable outcome on this relatively simple fire.

Cora Lynn Fire, New Zealand

In March 2001, the Cora Lynn fire burned 360 hectares of grass, native shrubs and native beech forest in steep, rocky terrain. The fire burned for 10 hours with full suppression consisting of several helicopters and ground personnel. The native beech forest fuel type was interesting to model because there are no straightforward fuel models in the Canadian or U.S.-based systems. FARSITE used a moderate load humid timber shrub model (TU2) with increased fuel moisture to model the very slow fire spread appropriately. Prometheus used the custom New Zealand indigenous forest model based on FBP's M-2 (mixed hardwoods), but found the fuel model was spreading fire too rapidly. With some minor calibration and fuel model adjustments from brush to rock, both simulators were able to model the Cora Lynn Fire reasonably well.

Wangary Fire, Australia

The Wangary Fire burned on the Lower Eyre Peninsula in South Australia in January 2005. The fire spread rapidly in grass, brush, and forested fuel types to a final extent of 77,000 hectares. Suppression efforts were hampered by extreme fire behavior during the second burning period when a wind shift pushed the left flank east and northeast. This simulation was unique in that the previous day's burned area was provided, and in that multiple ignition points needed to be modeled only for the second burn period.

The differences between observed and modeled perimeters were within acceptable limits. Prometheus over-predicts the fire's southern edge; this may be because the FBP grass fire model, which was set at 95% curing, is known to over-predict under these conditions (Figure 3). FARSITE uses the stylized Rothermel-based grass model GR6 (moderate load, humid climate grass, dynamic) (Scott and Burgan 2005). The FARSITE simulation more closely approximates the fire's southern edge; however, the fire was simulated using the same ignition time for the four ignition points. Prometheus used the actual, varied ignition times for the four ignition points, and this difference will certainly have an impact on the generated perimeters.

FARSITE over-predicts the northwest fire edge where suppression activities were occurring, while Prometheus did so to a lesser degree. This may also be accounted for by differences in the fuel models and in ignition times. The potential actual fire growth in this direction is difficult to approximate when one considers the amount of suppression that took place in that area.

Prometheus over-predicts the fire at the northeast edge, while the FARSITE simulation is closer in that respect. FARSITE was running at a coarse tolerance for vertex separation (400m); Prometheus was running at a finer tolerance (50m). Interestingly, through our discussions of this simulation we determined that the vertex resolution was deemed inconsequential due

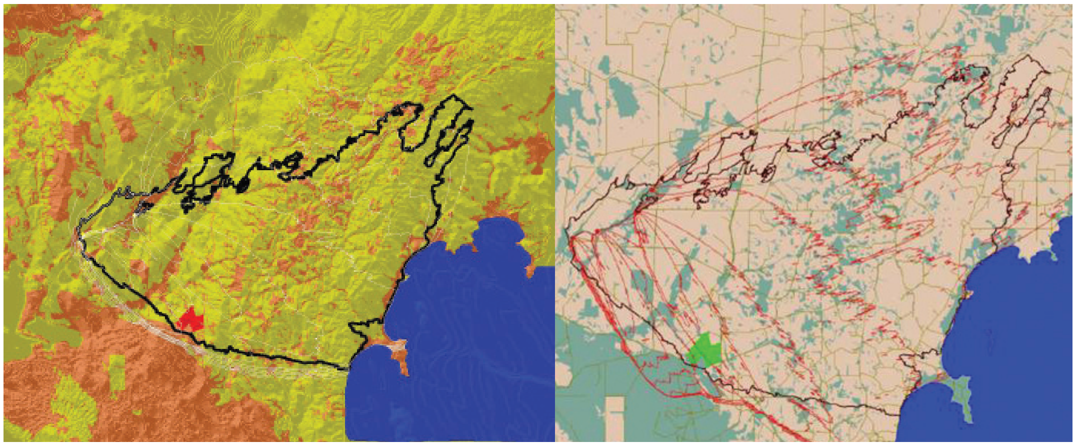

Figure 3—FARSITE (left) and Prometheus (right) modeled Australia's Wangary Fire. Although there are differences in the fire spread model, how suppression was modeled in each simulator, and the starting times of the spot fires, the resulting perimeters still coincide reasonably well with the final fire edge (black).

to the low variability of the spatial data. Despite these differences, both of the modeled perimeters successfully approximated the final fire perimeter in a reasonable length of time.

Discussion: What We Learned

The lack of a site-specific fuel model and weather data was a concern, but our coarse approach regarding crosswalking land cover classes to fuel models proved adequate. Site visits were instrumental in determining the most appropriate interpretation of wind observations several kilometers away from the fire. This was imperative because the simulations were not useful without local wind data. The Craigeburn fire illustrates this well; local winds influencing the final fire shape are impossible to know.

The choice of grass models proved less important than expected since they could be easily manipulated to spread faster or slower through moisture content values during the calibration process. There is great latitude in deciding what fuel types to use, because a particular fire can be modeled well using a variety of combinations of fuels, winds, and moisture contents that are all within the uncertainty of actual data. The coarse vegetation maps and fuel model crosswalks proved adequate for representing fuel conditions in fires we modeled, but they will constrain use of simulators in diverse fuel complexes—a known problem for any simulator.

The ability to adapt the simulators to the local fire environments was mixed. It was necessary to create solar radiation effects from the north rather than the south and simulating summer day lengths in January. Entering a negative latitude in FARSITE changed the sun angle and automatically changed day length for the fire date. Adding six months to the date, and selecting New Zealand and Australian time zone settings in Prometheus were necessary to simulate appropriate conditions. FARSITE was unable to readily input weather streams that crossed into a new calendar year, which was problematic for fires igniting on January 1 and requiring three prior days of fuel conditioning weather data. Several of these identified problems have since been fixed in both simulators.

The disadvantage of both simulators was that each is built around one set of fire spread equations. FARSITE currently implements fire behavior models based on Rothermel (1972), and Prometheus implements fire behavior models based on Canadian fire spread equations (Forestry Canada Fire Danger Group 1992). Although fire spread equation coefficients can be user-manipulated to some degree, neither Prometheus nor FARSITE supports the entry of fully customized fire spread equations with varying parameters. Though some simulation inputs were easily manipulated, the ability to use locally developed equations is an important feature of any Australasian spatial fire simulator because several varied fire spread equations are in use or under development.

Each fire simulator handles timesteps and vertices differently. FARSITE uses an internal dynamic time step that is adjusted to control spatial resolution of the calculations for execution performance. Prometheus employs user-defined fixed timesteps for direct control. FARSITE merges fires and eliminates vertices on the fire perimeters that cross, whereas Prometheus retains the separate identity of individual fires and renders vertices inert. Prometheus uses many more vertices than FARSITE to represent the active fire front. Prometheus by default uses a vertex resolution that matches that of the grid data, and FARSITE by default uses a coarser resolution to address performance concerns, and to intentionally ignore minor variations in the grid fuel map.

In Prometheus and FARSITE, the final modeled perimeter is strongly influenced by several user inputs and settings that are impossible to separate from model error. These various inputs and settings are necessary to allow experienced users to approximate the local environmental variability as closely as possible and to control the computational intensity of the simulation to match time or computer constraints. Interestingly, the two models do not share the same reconfiguration options. This fact complicated direct comparisons of outputs.

Even though both simulators were developed independently, they share very similar functionalities and user interface designs. The differences were influenced in part by their operational roles in their respective countries. FARSITE is more adept at handling different weather stream formats and has more displays of different data. Prometheus can simultaneously simulate and display outputs from differently configured scenarios (variations in user settings, and in spatial and temporal data are allowed) for direct comparisons within the model.

Direct comparison of Prometheus and FARSITE is difficult because modeling fire perimeters is as much art as science. We cannot conclude whether one application is better based solely on the ability to predict fire spread, size, and shape due to differences in underlying fuel models and computation implementations, and an inability to separate user error from model error. Although both models performed reasonably well, they still required minor tuning with respect to the computational implementations of the fuel equations. This suggests that these models should be operated by expert users who are aware of their intricacies. Exact agreement between models and against the observed fires is not possible for many reasons, but the degree of similarity between these systems suggests that the application of Huygens' principle and assumed independence of segments of the fire front is justified for the grass fires tested. Thus, we conclude that it was more important to choose an application compatible with current data availability, current fire management systems, and that can be modified to use unique and varied fire spread equations.

This seminar was an excellent technology transfer opportunity. Modeling fires together in one room with different models was more advantageous than we anticipated; the opportunity to run the applications side-by-side is what made this seminar extraordinary. Modelers gained an appreciation for the need to accommodate a variety of different fire spread equations and parameters in one fire spread simulation system. Application developers, computer scientists, fire managers, fire behavior scientists, and GIS specialists learned from each other, were inspired to try new approaches to problems, considered new concepts, and established relationships with international fire modeling colleagues.

Conclusions

Determining how to pursue adoption of a New Zealand or Australian spatial fire growth simulator requires further consideration and will take place over the next several months.

This seminar provided a first step in sharing available information. Although the scale of wildland fire in New Zealand versus Australia differs significantly, their fire management and research institutions are geographically and politically linked. Currently, there is no spatial fire spread simulator used in either country, but interest is growing among Australasian fire managers to adopt a common tool to enhance decision-making for operations and planning, especially with regard to reconstructing fire events to measure the success of suppression operations or investigate potential fire behavior. Among the numerous considerations, the flexibility in incorporating local fire behavior models into one of these systems will be important. Simulators such as FARSITE and Prometheus both appear to be well suited to modeling fires in New Zealand and Australia.

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