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Modeling fire in semi-desert grassland/oak woodland: the spatial implications

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Abstract

Fire-evolved forests that historically had high fire return intervals (< 100 years) in the western United States are currently overstocked with fuels due to a century or more of fire suppression and anthropogenic modification. Additionally, some western rangelands have changed composition from fire maintained grasslands to grazed shrublands. Land managers are beginning to reintroduce fire to these ecosystems as a functional component. Estimating fire behavior through the use of computer simulations is one tool to assist in planning management-ignited fire. We evaluated the sensitivity of the fire model FARSITE to the level of detail in the fuels data, both spatially and quantitatively, to better understand requirements for mapping fuels to produce accurate fire simulations. Simulated fires generated using site specific fuel models mapped at 30 m and degraded to 210 m were compared to fires simulated using standard generic Northern Forest Fire Laboratory (NFFL) fuel types. Eight classes of surface fuels were mapped by classification of satellite imagery with an overall accuracy of 0.78. A percent tree canopy cover map was created from digital orthophotos using a linear regression model with an $R^2_{adj} = 0.93$ of field sampled percent canopy cover data to a tree canopy shadow model. The dominant site specific fuel model (63% cover) was found to agree with the most suitable NFFL fuel model. Site specific fuel models mapped at fine resolution were found to produce statistically smaller fire areas than those produced with generic fuel models mapped at a fine scale and site specific fuels mapped at a coarse scale. In the worst case scenario (low fuel moistures and high wind speeds) the average fire size was about 20% larger with the fuel map using NFFL fuel models than with the fine scale map using site specific fuel models. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fire modeling; FARSITE; Fuel models; Fuels mapping; Sensitivity analysis; Spatial resolution; Scale; Semi-desert grassland

1. Introduction

Prior to the introduction of large numbers of domestic livestock on the ranges in the southwestern United States during the late 1800s, fires appear to have been a frequent characteristic of

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the semi-desert grassland and adjacent woodlands (Leopold, 1924; Humphrey, 1958; Bahre, 1985; Bock and Bock, 1988; Swetnam et al., 1992). Most researchers today agree that wildfire suppression in conjunction with overgrazing has led to the invasion of the grasslands by woody genera such as *Prosopis*, *Acacia*, *Mimosa*, and *Gutierrezia* in drought susceptible grasslands in the Southwest (Sauer, 1950; Humphrey, 1963; Wright and Bailey, 1982; Bahre, 1991; McPherson, 1995). Individual grassland fires historically covered tens of thousands of hectares in southeastern Arizona and southern New Mexico, but fire sizes today tend to be small due to fire suppression and removal of fine fuels (Bahre, 1985). Restoring the historic fire return interval is thus only possible through the use of management-ignited prescribed fire.

Even though public perceptions of wildland fire have changed in recent years to accept fire as beneficial, the public perceives that mitigating fire risk and fiscal restitution for fire damage is a public or governmental responsibility (Cortner et al., 1990). It is advantageous to all parties involved with prescribed fire to be informed about fire behavior characteristics. Estimates of rate of spread and intensity are used to define the conditions under which a management-ignited fire will be conducted. Estimating fire behavior through the use of computer simulations is an appropriate tool for the planning of management-ignited fire (Rothermel, 1972). Modeling of fire is not a substitute for experience, but it does provide a way to quantify and predict fire behavior based upon environmental variables (Pyne et al., 1996).

Fire behavior models are typically placed into two broad categories: physical, or probabilistic. Physical models are those based upon mathematical analysis of the fundamental and chemical process of fire spread. Sometimes observations from small-scale experimental fires are used to parameterize the formulas in addition to measurements of the fuel bed, weather, and topography. Probabilistic models are statistical descriptions of experimental wildland fires and make no attempt to include any of the physical mechanisms that control the fire process (Perry, 1998). Physically based models can be used to predict incremental fire spread and fireline intensity. Results can be related to the processes controlling fire spread. Probabilistic models, however, attempt to characterize broad-scale heterogeneity and resulting burn pattern by adjusting probabilities, making results difficult to use in making inferences about physical processes (Finney, 1998). Probabilistic models also are difficult to parameterize without an extensive fire history database and can only be used cautiously outside the baseline conditions (Perry, 1998). Hargrove et al. (2000) for example, required a database of 235 lightning caused fires to parameterize the spatially explicit probabilistic model EMBYR to model possible fire patterns in Yellowstone National Park, USA.

Versions of the physically based fire behavior model developed by Rothermel (1972) are today the most widely used fire simulation models (Weise and Biging, 1997; Perry, 1998). Rothermel's equations are the basis for the point model BEHAVE fire prediction system used over the last 20 years by public land management agencies in the United States, including the National Park Service, Forest Service, and Bureau of Land Management (Andrews, 1980, 1986). In addition, Rothermel's equations have been used by many researchers to model fire behavior. Wu et al. (1996) implemented Rothermel's equations in modeling high resolution (20 m) two-dimensional fire spread patterns in the Everglades freshwater marsh in South Florida, USA. Rothermel's equations have been incorporated in a spatially explicit forest gap model for the purpose of modeling fire effects due to fireline intensity (Miller and Urban, 1999).

Recently, FARSITE (Fire Area Simulator) (Finney, 1996) has become a widely used fire behavior model by public land management agencies in the United States (Keane et al., 2000). FARSITE was initially developed for planning and operational management of prescribed natural fires (Finney, 1996). As a spatially explicit two-dimensional fire growth computer model, FARSITE implements the Rothermel (1972) equations for calculating surface fire spread rate and Richards, (1990, 1995) formulation of Huygens' principle for calculating surface spread pattern. In addition, models for crown fire (Van

Wagner, 1977, 1993) and spotting (Albini, 1979) are integrated making FARSITE a comprehensive fire prediction model (Finney, 1998). FARSITE has been used as the fire spread simulator in a spatially explicit fire succession model (Keane et al., 1999) and to evaluate effects of silvicultural and fuels treatments on potential fire behavior (Stephens, 1998). FARSITE has been previously validated using fires in conifer forests of Yellowstone and Glacier National Parks (Finney and Ryan, 1995), and in Sequoia National Park (Finney, 1993), but its use in the southwestern United States has not been documented.

Typical of spatial fire models, FARSITE assumes homogeneity within the scale of the mapping unit used to describe the fuels. In the middle 1970s the Northern Forest Fire Laboratory (NFFL) standardized fire behavior predictions by defining fuel parameters of 13 fire behavior fuel types and labeled them fire behavior fuel models (Albini, 1976). Although, it has been claimed that accurate mapping of fuels can improve the accuracy of fire behavior modeling (Albini, 1976; Finney and Ryan, 1995), there have not been any published studies that have compared results of fire modeled with fuels mapped at a fine scale of spatial detail versus coarse detail or using the standard NFFL fire behavior fuel models versus site specific fuel models.

In this research, we evaluate the sensitivity of FARSITE to the level of detail in the fuels data, both spatially and quantitatively, providing land managers knowledge on which to base decisions about the effectiveness of detailed fuels mapping in modeling fire spread. We produced two fuel maps from field sampled site specific fuels mapped at different scales, and one map using the NFFL standard fuel models. Sizes of simulated fire areas resulting from using these fuels maps as input to FARSITE are compared.

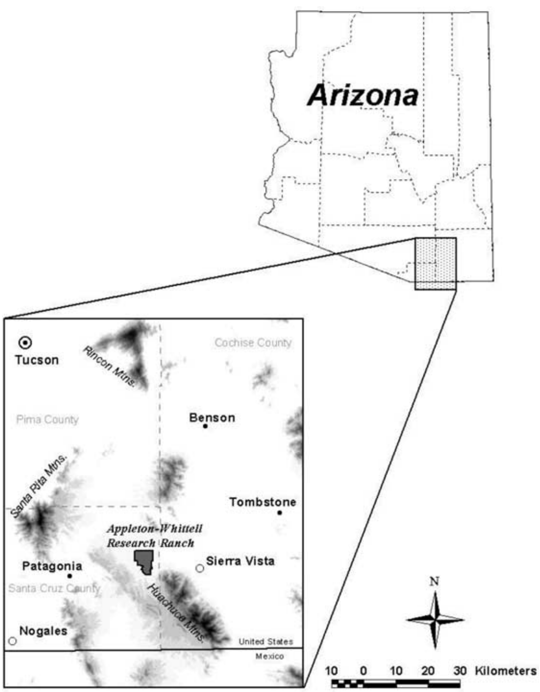

Fig. 1. Location of the Appleton–Whittell Research Ranch in southeastern Arizona, USA.

2. Methods

2.1. Study area

This study was conducted at the Appleton–Whittell Research Ranch (hereafter, referred to as the Ranch) located on the northwest edge of the Huachuca Mountains 100 km southeast of Tucson, AZ (Fig. 1). In 1968, the Appleton family discontinued grazing on their ranch and asked the National Audubon Society to manage the ranch as an ecological research station and preserve. It has not been disturbed by livestock management practices since. The 3,200 ha ranch is composed of land owned by the USDA Forest Service, the USDI Bureau of Land Management, and private land. Today the Ranch is the largest ungrazed section of privately managed grassland in Arizona and perhaps the Southwest (Bahre, 1977). Vegetation communities are primarily semi-desert grassland and Madrean evergreen woodland ecosystems dissected by riparian corridors. Fire has largely been eliminated from the Ranch since the middle 1800s due to grazing and fire suppression.

2.2. Fire simulation model

FARSITE runs in a user-friendly Windows environment with pull-down menus and real-time on-screen graphics. Required input parameters include descriptions of the topography, fuel conditions and amounts (including tree canopy and surface fuels), and weather. Topography and fuels are defined using raster geographical information system (GIS) data while wind, humidity and temperature are defined using data streams. Required spatial fuels descriptions include percent canopy cover and distribution of surface fuels. Tree canopy height, height to base of crown, and crown bulk density may be spatial or constants. Topography expressed as elevation, slope, and aspect are required to be spatially defined and are typically derived from a digital elevation model (DEM) (Finney, 1998).

Fire perimeters and areas resulting from FARSITE simulated fires at each, or user selected time steps, are output as GIS polygon layers. Available raster outputs include time of arrival, fireline intensity, flame length, rate of spread, heat per unit area, direction of spread, and an indicator of fire type (surface, passive crown, or active crown).

How FARSITE uses each input layer is discussed in the following sections along with how those layers were created for this research. This research was conducted using FARSITE version 3.0. The latest version and documentation may be found at http://www.farsite.net/.

2.3. FARSITE model inputs

U.S. Geological Survey 1:24,000 Level I DEMs at 30 m resolution were used to define the topography of our study area. The following sections detail development of the remaining input data used in this research.

2.3.1. Tree canopy characteristics

A spatial map of percent canopy cover is used by FARSITE to determine an average shading of the surface fuels that affects fuel moisture calculations. It is also used to help determine a wind reduction factor that decreases the input reference wind speed measured at 6.1 m above the vegetation crown height to a level that affects surface fire. The height to the bottom of the tree crown is used along with surface fire intensity and foliar moisture content to determine a threshold for transition to crown fire. Crown bulk density is used to determine a threshold for achieving active crown fire (Finney, 1998). Crown fire was not modeled in this research. Therefore, we did not develop spatial layers for crown base height and bulk density. An average tree height derived from field data was used for crown height.

Panchromatic digital orthophoto quarter quadrangles (DOQQs) with 1 m resolution were used to estimate the percent tree canopy cover. A computer automated interpretation of the DOQQs was implemented and trained on field sampled data to develop a model for percent canopy cover supplemented with a canopy shadow model that accounted for topography. The computer algorithm employed a linear contrast threshold stretch (Schowengerdt, 1997) to identify tree-plus-shadow pixels. The stretched 1 m resolution image was integrated over 30×30 m^2 pixels. The 30 m pixel size was chosen to match the DEM and Landsat TM data used in the project. The brightness of the 30 m pixels represented the percentage of tree and shadow pixels in the original image over a 900 m^2 area.

To determine the actual percent cover from the canopy-plus-shadow image, a tree canopy shadow model was used to account for shadow due to the tree and topographic effects (Strahler et al., 1988; Franklin et al., 1991). A generic tree-plus-shadow due to topography and tree-plus-shadow without topography were modeled with average tree characteristics measured in the field and a DEM. Most tree cover on the Ranch consists of linear swathes of trees along drainages and north facing slopes. Representative locations within homogeneous areas were chosen to measure tree canopy characteristics and percent cover with line intercept transects (Canfield, 1941).

The ratio of the computer generated tree-plus-shadow image to the true percent canopy cover measured in the field should be the same as the ratio of a tree-plus-shadow due to topography to a tree-plus-shadow without topography. The two ratios were regressed ($R^2_{adj} = 0.93$) and the linear

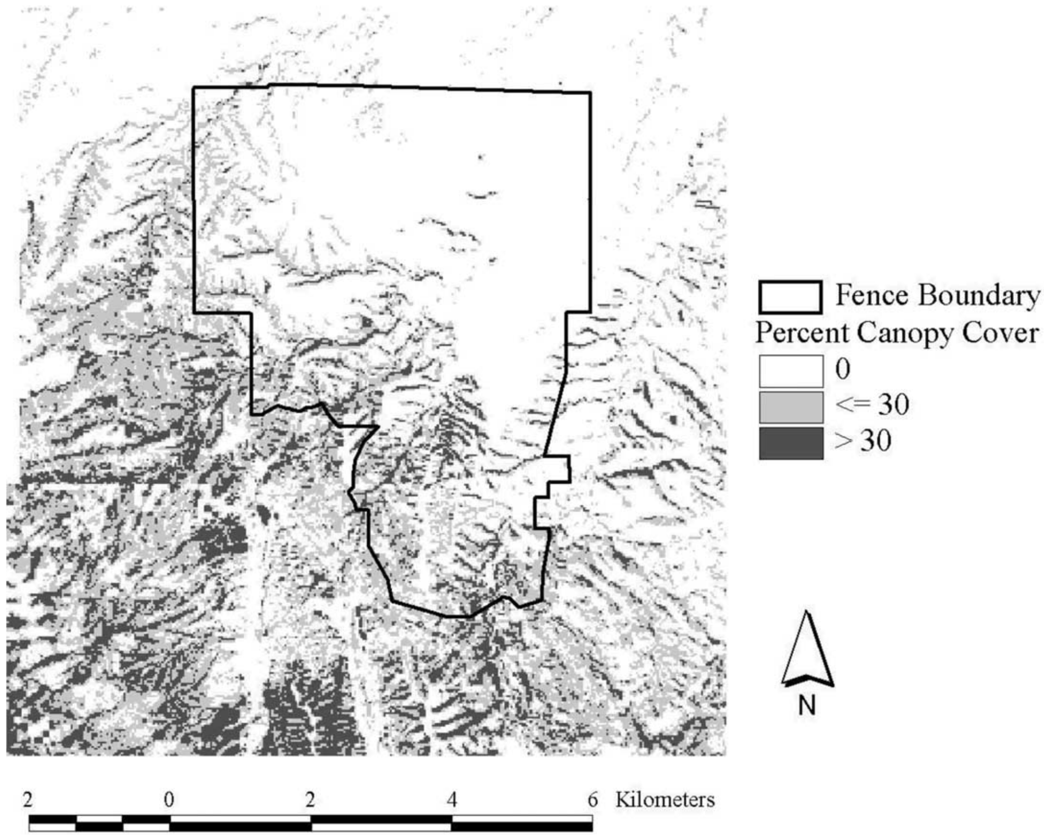

Fig. 2. Percent canopy cover generated from a regression model of measured percent canopy cover and a tree canopy shadow model. The mean tree height for all trees measured was 6.16 m, the mean canopy diameter was 6.31 m, and the mean ground to crown height was 0.15 m.

equation solved for the true percent canopy cover. The linear model was applied to the whole canopy-plus-shadow image resulting in a spatial map of percent canopy cover (Fig. 2). Some areas were hand edited to remove percent canopy estimates where trees did not exist but had canopy cover estimates due to topographic shadows.

2.3.2. High resolution fuels map

A Landsat Thematic Mapper (TM) subscene from August 25, 1996 with a ground resolution of 30 m was used in this research to map fuels. The late August date was chosen to correspond with the phenology of the local vegetation after the summer rainy season. The image was geometrically and atmospherically corrected and values were converted to reflectances before being classified.

2.3.2.1. Classification training/accuracy assessment. An unsupervised classification was used initially to cluster similar spectral characteristics from the corrected Landsat image into a unique set of classes for field sampling of training sites to be used in a supervised classification (Yool et al., 1985). The Landsat data were the data were clustered into 100 unique clusters using the iterative self-organizing (ISO) clustering algorithm in the Environment for Visualizing Images (ENVI) software under WINDOWS95 (Kruse, 1998). Clusters of known similar characteristics based upon field experience were grouped into nine classes, each corresponding to a possible fuel model cover type. Fifty sites in each class were chosen randomly using IDRISI for Windows (Eastman, 1997) to be visited in the field. Each site was navigated to in the field using DOQQs and a Global Positioning System (GPS) receiver. After finding the site, a judgment was made based upon visual inspection of a 30×30 m^2 area as to which fuel model was appropriate. The size of the training sites corresponds to the pixel size of the Landsat image used in the classification. After visiting all of the sites, we selected eight classes for the final fuels map: Riparian Grass, Oak Woodland, Sparse Grass, Medium Grass, Dense Grass, Grazed Grass, Shrubs, and Bare Ground/Buildings.

Approximately 50 sites were randomly chosen within each class for accuracy assessment of the final fuels map. Since the Grazed Grass class did not exist within the Ranch boundary it was not verified in the field, leaving seven classes to be checked. A total of 351 sites were either visited in the field or checked against DOQQs. Field procedures for locating verification points were the same as for locating the training sites described above. The Oak Woodland and Riparian Grass classes were largely verified with DOQQs to save time in the field.

2.3.2.2. Fuels classification. The corrected Landsat TM data, DEM, estimated percent canopy cover, and field data were used to create a vegetation classification of the Ranch (Fig. 3a) corresponding to eight fuel model classes (Table 1). Principal components were computed for the Landsat data, resulting in six uncorrelated image components, isolating noise in the highest order component (Schowengerdt, 1997). The sixth component was eliminated, in effect filtering sensor noise from the original data. The first five components, elevation, and percent canopy cover were used in a supervised maximum likelihood classification to derive the final fuels map (Jensen, 1996). Upon analysis of the spectral characteristics of the training classes, the Riparian Grass and Medium Grass classes were found to be bimodal. The Riparian Grass is grazed outside the Ranch boundary, therefore appearing to be much greener than the Riparian Grass on the Ranch in the image. The Medium Grass class on the southern end of the Ranch contains more tree cover than the northern end making those training sites appear greener in the image. The Riparian Grass and Medium Grass classes were each split into two classes during classification to satisfy the Gaussian assumptions of the maximum likelihood classification and recombined after classification (Jensen, 1996).

Table 1
Vegetation fuel classes and corresponding fuel models

Vegetation class	Fuel model
Riparian Grass (*Sporobolus wrightii* Munro)	Riparian Grass
Sparse Grass	Sparse Grass
Medium Grass	NFFL 1
Dense Grass (primarily *Eragrostis curvula* Schrad.)	Dense Grass
Shrubs (primarily *Mimosa* spp. and *Caliandra* spp.)	Shrubs
Oak Woodland >30% canopy cover	Oak Woodland
Grazed Grass	Bare Ground
Bare Ground/Buildings	Bare Ground

2.3.3. Site specific fuel parameters

Fuel parameters provide a physical description of fuel type or class. These parameters influence surface fire behavior. The set of parameters for a fuel type has traditional been called a fuel model by fire behavior scientists (Albini, 1976). Fuel models incorporate parameters such as fuel particle surface-tovolume ratios, loading of the fuel components in size classes, and proportions of live and dead components. Fuels were measured on the Ranch using procedures based upon Brown et al. (1982). Field sampling was conducted to measure the fuels for six of the eight fuel classes. Grazed Grass was not sampled since it did not occur within the Ranch fence boundary. Bare Ground/Buildings class did not require field sampling and was modeled as bare ground. In addition to the fuel parameters specified by Brown et al. (1982), fuel bed depth, shrub density class, shrub type, and percent cover were recorded specifically to develop custom (site specific) fuel models using procedures as described by Burgan and Rothermel (1984).

Site specific fuel models (Table 2) were created using the NEWMDL and TSTMDL programs in the BEHAVE system (Burgan and Rothermel,

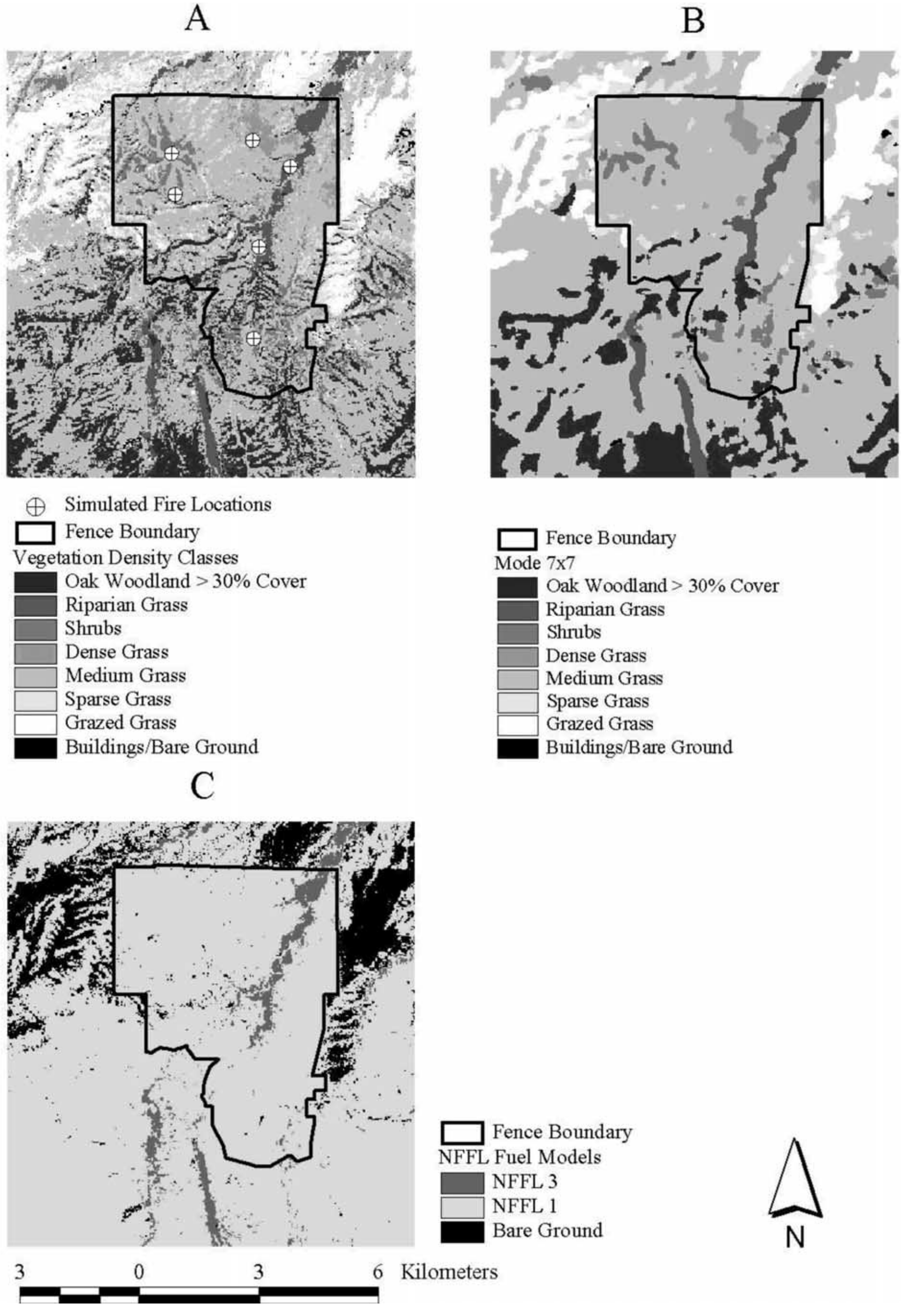

Fig. 3. Fuels maps: (a) high resolution custom fuels map based at 30 m mapping resolution derived from a Landsat TM image, August 25, 1996 (overlaid with random fire start locations used in the simulations); (b) low resolution custom fuels map at 210 m mapping resolution (30 m pixels) fuels map generated by degrading the high resolution custom map with a 7×7 mode filter; (c) fuels map using NFFL fuel models at 30 m mapping resolution.

Table 2
NFFL and site specific fuel models for the Appleton–Whittell Research Ranch

	Riparian Grass	Dense Grass	Medium Grass (NFFL 1)	Sparse Grass	Oak Woodland	Shrubs	NFFL 3
Loads (kg/ha)							
1 h	13 450	8967	1659	672	4954	3049	6747
10 h	0	0	0	0	90	179	0
100 h	0	0	0	0	67	0	0
Live herbaceous	2242	672	0	0	0	0	0
Live woody	0	0	0	0	22	90	0
Surface/volume ratios[a]							
1 h	1500	2500	3500	3500	3000	3300	1500
Live herbaceous	1350	2200	190	0	0	0	190
Live woody	0	0	190	0	3000	1500	190
Sigma[b]	1480	2481	3500	3500	2998	3270	1500
Other							
Depth (m)	0.9	0.45	0.30	0.12	0.24	0.24	0.76
Heat content[c] BTU/kg	3636	3636	3636	3636	3636	3636	3636
Extinction moisture[c] (%)	25	25	12	12	12	12	25

[a] Based upon NFFL 1 and typical surface-area-to-volume ratios from Burgan and Rothermel (1984, p. 24).
[b] Represents the overall surface-area-to-volume ratio for the fuel model.
[c] Primarily derived from NFFL 1 since the 1 h fuels are all primarily the same types of grasses. The extinction moisture for NFFL 3 was used for Dense grass and Riparian Grass.

1984). The NEWMDL program allows the initial definition of fuel models using the field sampled data. TSTMDL provides the ability to test fuel models under various environmental conditions, examine fire characteristics and modify fuel models. After the fuels were sampled in the field and fuel loads were calculated it was determined that NFFL fuel model specified by Anderson (1982) for the grasslands in southeastern Arizona (NFFL 1) actually represented the Medium Grass class so it was used for the site specific fuel model. Table 3 summarizes fire characteristics for the listed environmental conditions output from the TSTMDL program for each fuel model.

2.3.4. Meteorological data

Meteorological data required by FARSITE are grouped into three basic types: weather, wind, and fuel moistures. Weather data consist of minimum and maximum daily air temperature, percent humidity, precipitation, cloud cover, and the times these occur. Wind data include direction and speed versus time. Fuel moistures are initial conditions at the time of simulation for each down woody fuel size class. Weather parameters are used to determine fuel moisture conditions at each time step during the simulation. Fuel moistures influence fuel ignition. Wind parameters influence direction and speed of fire spread. Even though weather and wind are spatial in reality, they are most often described with single point values since they are the most difficult to measure in fine spatial detail and they change over time much more quickly than the topography or fuels (Finney, 1998).

A first order weather station was installed at the Ranch during the summer of 1997. Weather and wind parameters recorded by the Ranch weather station for April through August 1998 were used to define typical early summer fire season weather conditions. Although, site specific weather data were only available for one summer, we believe these data were typical of early summer conditions. Fuel moisture data are not recorded at the Ranch. However, fuel moisture data are routinely collected at Coronado National Memorial located at the southern end of the Huachuca Mountains about 30 km from the Ranch, and Chiricahua National Monument located at the north end of the Chiricahua Mountains about 100 km from the Ranch. The memorial and monument are at about the same elevation as the Ranch (1400–1500 m) and in semi-desert grassland. Fuel moistures for April through July 1997 collected either at the Monument or Memorial were used to define typical values at the Ranch.

2.4. Fire spread simulations

Fuel, topography, and weather are the three environmental variables that influence fire spread. From a fire viewpoint, topography is constant over time, but varies over space. Fuel varies over space and time. Weather is the most variable, rapidly changing over space and time (Pyne et al., 1996). Since we were testing hypothesis involving fuels, we evaluated differences in mapped fuels under various weather (wind speed, direction and fuel moisture) and topographic conditions (multiple ignition locations).

Simulations were run using three different fuel maps. All other input data remained the same for all simulations. Two maps, the fuels map at 30 m mapping resolution (Fig. 3a) and a map created by degrading the 30 m fuels map with a 7×7 mode filter (Fig. 3b), were used to evaluate effects of fuel map spatial resolution. The 7×7 mode filter in effect created polygons of 210 m, approximating the 250 m pixel size of the NASA MODIS sensor. The third map (Fig. 3c) was composed entirely of NFFL fuel models 1 and 3 to compare detailed site specific fuel models with generic fuel models. Model resolution (pixel size) for all maps was held at 30 m to preserve consistency in model calculations during the fire modeling for all three fuel maps. Simulations were run at six randomly selected locations (Fig. 3a), four wind directions, three wind speeds, low and medium fuel moistures, and with three fuel maps for a total of 432 simulations. Fire areas were recorded at 2, 4, 6, and 8 h into the simulation for fires using the custom fuel map at 30 m resolution and at 8 h into the simulation for all others. Maximum and minimum daily percent humidities for dry conditions were 15 and 7% and for medium conditions, percent humidities were 50

Table 3
Fuel model fire characteristics for each site specific fuel model generated by TSTMDL

	Riparian Grass	Dense Grass	Medium Grass (NFFL 1)	Sparse Grass	Oak Woodland	Shrubs	NFFL 3
Environmental data							
10 h fuel moisture (%)	2	2	2	2	2	2	2
100 h fuel moisture (%)	6	6	6	6	6	6	6
Live herbaceous fuel moisture (%)	40	35	NA	NA	NA	NA	NA
Live woody fuel moisture (%)	NA	NA	NA	NA	77	77	NA
Wind (km/h)	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Slope (%)	0	0	0	0	0	0	0
Fire behavior results for 1 h time-lag fuel moisture of 2%							
Rate of spread (m/min)	32	21	18	7	12	13	32
Flame length (m)	7	4	1	0.5	2	2	4

and 20%, respectively. All FARSITE simulations were run with the crowning algorithms disabled since the study site is a woodland of limited canopy cover.

3. Results and discussion

3.1. Fuels classification accuracy evaluation

A total of 351 randomly located sites were either visited in the field or verified using DOQQs. The user's accuracy (a measure of commission error) and the producer's accuracy (a measure of the omission error) are listed by class in Table 4 (Congalton and Green, 1999). During the accuracy assessment, three verification sites were found not to fall into one of the eight fuel classes. Two of those sites were riparian areas containing vegetation other than Riparian Grass, and the third comprised large trees next to a residence. These three sites were put into an 'other' class for accuracy assessment. Most of the user's accuracies ranged between 80 and 88%, with the Shrubs and Dense Grass class accuracies around 65%. An overall classification accuracy of 78% was achieved, comparing favorably with other results in grasslands. Overall classification accuracies between 76.5 and 82.3% have been reported in tallgrass prairie when distinguishing only two categories of grassland quality (Lauver and Whistler, 1993). Estimates of the kappa coefficient (KHAT) are listed for user's and producer's accuracy. The kappa coefficient, which ranges between 0 and 1, is a conservative measure of the difference of the actual agreement between reference data and an automated classifier, and the chance agreement between the reference data and a random classifier (Congalton et al., 1983). An overall KHAT of 0.73 was achieved, meaning that the classification accuracy was 73% greater than chance.

The use of the percent canopy cover generated from DOQQs in the classification significantly increased the accuracy of the Oak Woodland class. However, 20% of the Oak Woodland verification sites fell into the Medium Grass class due to possible registration errors, topographic shadows affecting the percent canopy cover layer, or locating the site in the field due to GPS error. Misclassified Oak Woodland sites generally had trees on the site or very close, and those that had trees were less than 30% tree cover. Most misclassifications arose from confusion between Dense Grass, Sparse Grass, and Shrub classes, with the Medium Grass class. Small registration errors, changes in grass cover due to the 3-year difference between the Landsat image date and the field work, and GPS errors were possible contributors to the errors.

3.2. Fire simulations

Simulations were run using three different fuel maps: (1) the original fuels map at 30 m resolution (Fig. 3a); (2) a 210 m resolution map (Fig. 3b); and (3) a map composed entirely of NFFL fuel models 1 and 3 at 30 m resolution (Fig. 3c). Fire perimeters (Fig. 4) of simulated fires demonstrate how fire is controlled by wind, fuels and topography. The shapes of fires in the northwest corner of the Ranch are mostly controlled by wind direction and wind speed in Shrub and Medium Grass fuel models. Fires ignited in the northeast corner of the Ranch are more linear, following the north-north-east direction of Riparian Grass in O'Donnell Creek due to the higher spread rates of the Riparian Grass fuel model. Simulated fires are smaller on the south end of the Ranch, where more trees and dissected topography prevail. Fire spread was slower due to ridgelines, lower temperatures and higher humidities resulting from increased tree cover.

Hargrove et al. (2000) concluded that fuel moisture had a greater effect on simulated fire sizes than wind speed when comparing results from multiple wind speed and moisture classes. Our results show that fire sizes are equally co-dependant on both wind speed and fuel moisture (Fig. 5). At short time periods and low wind speeds, the low and medium fuel moistures produced fires of about the same size. However, the average low fuel moisture fire was about half the size of the average medium fuel moisture fire with the highest simulated winds. Fires increased exponentially in size with increasing wind speed, reflecting

Table 4
Classification error matrix for the high resolution fuels map

	Riparian Grass	Oak Woodland	Dense Grass	Medium Grass	Sparse Grass	Shrubs	Bare ground/ buildings	Other	Total	User's accuracy (%)	KHAT
Riparian Grass	54	0	4	3	0	2	0	2	65	83	0.80
Oak Woodland	0	40	0	10	0	0	0	0	50	80	0.77
Dense Grass	0	0	32	17	0	0	0	1	50	64	0.60
Medium Grass	0	0	1	42	7	0	0	0	50	84	0.76
Sparse Grass	0	0	0	10	66	1	2	0	79	84	0.79
Shrubs	0	1	0	12	4	32	0	0	49	65	0.61
Bare Ground/ Buildings	0	0	0	0	1	0	7	0	8	88	0.85
Other	0	0	0	0	0	0	0	0	0	0	0.00
Total	54	41	37	94	78	35	9	3	351		
Producer's accuracy (%)	100	98	86	45	85	91	78	0		78	
KHAT	1.00	0.97	0.84	0.35	0.80	0.90	0.66	0.00			0.73

(columns, field sampled reference data; rows, classified image data).

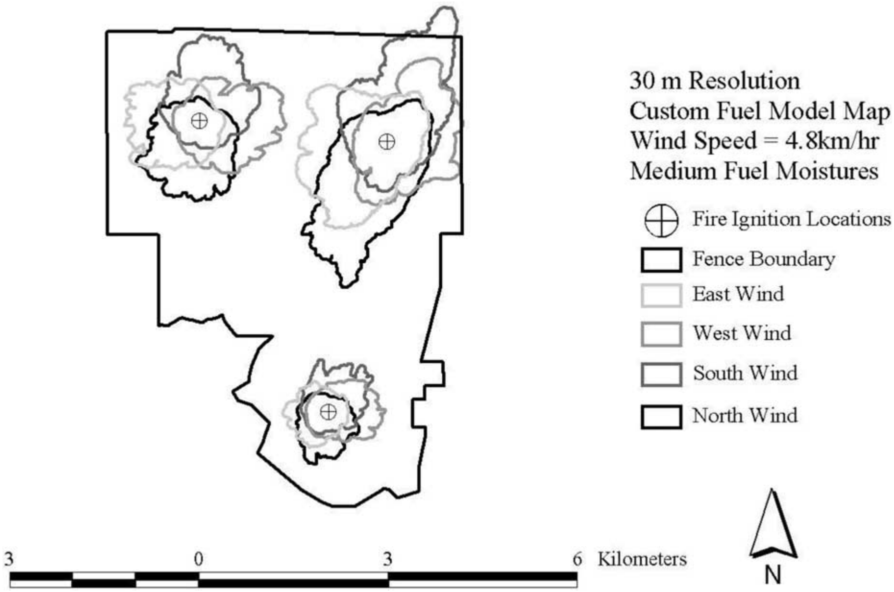

Fig. 4. Typical simulated fire perimeters from FARSITE using the high resolution custom 30 m fuel model map and medium initial fuel moistures.

the fire spread equation (Rothermel, 1972). Fires were a factor of 10 larger for wind speeds of 8 km/h than 1.6 km/h at both fuel moistures and for all fuels maps. On average, the NFFL fuels map had the larger burned areas followed by the custom 210 m fuels map, with the custom 30 m fuels map having the smallest areas burned on average.

The coefficient of variation calculated on all simulations grouped by time, wind speed, and fuel moisture conditions, decreases with increasing time and wind speed indicating that there is more variability in fires with short time spans and slower wind speeds (Fig. 6). This may be due to one or two situations depending on the wind direction and fire ignition location: (1) the simulated fires reached the boundary of Ranch where the area outside the Ranch boundary was grazed (modeled as bare ground) so the fire did not expand past the Ranch boundary; or (2) the fire reached the edge of the fuels map, therefore artificially restricting the fire size.

A non-parametric Wilcoxon matched pairs test was used to determine whether sizes of simulated fire areas were significantly affected by differences in spatial detail and fuel model accuracy (Conover, 1971). Comparisons were made for three pairs of fuel map combinations: (1) custom fuel models at 30 m resolution versus custom fuel models at 210 m resolution; (2) custom fuel models at 30 m resolution versus NFFL fuel models; and (3) custom fuel models at 210 m resolution versus NFFL fuel models (Table 6). The null hypothesis in each case was that the means of the fire areas were the same for the two fuel maps. The null hypothesis was rejected in all but three cases: (1) NFFL versus custom fuel models at 210 m resolution, low fuel moistures, and wind speed of 1.6 km/h; (2) NFFL versus custom fuel models at 210 m resolution, medium fuel moistures, and wind speed of 1.6 km/h; and (3) NFFL versus custom fuel models, medium fuel moistures, and wind speed of 4.8 km/h. The NFFL versus custom fuel models at 210 m resolution, low fuel moistures, and wind speed of 4.8 km/h was barely rejected at a p-level $= 0.046$. Essentially, the NFFL fuels map and custom fuels map at 210 m resolution produced equivalent results at the low and medium wind speeds. All other combinations were significantly different at all wind speeds.

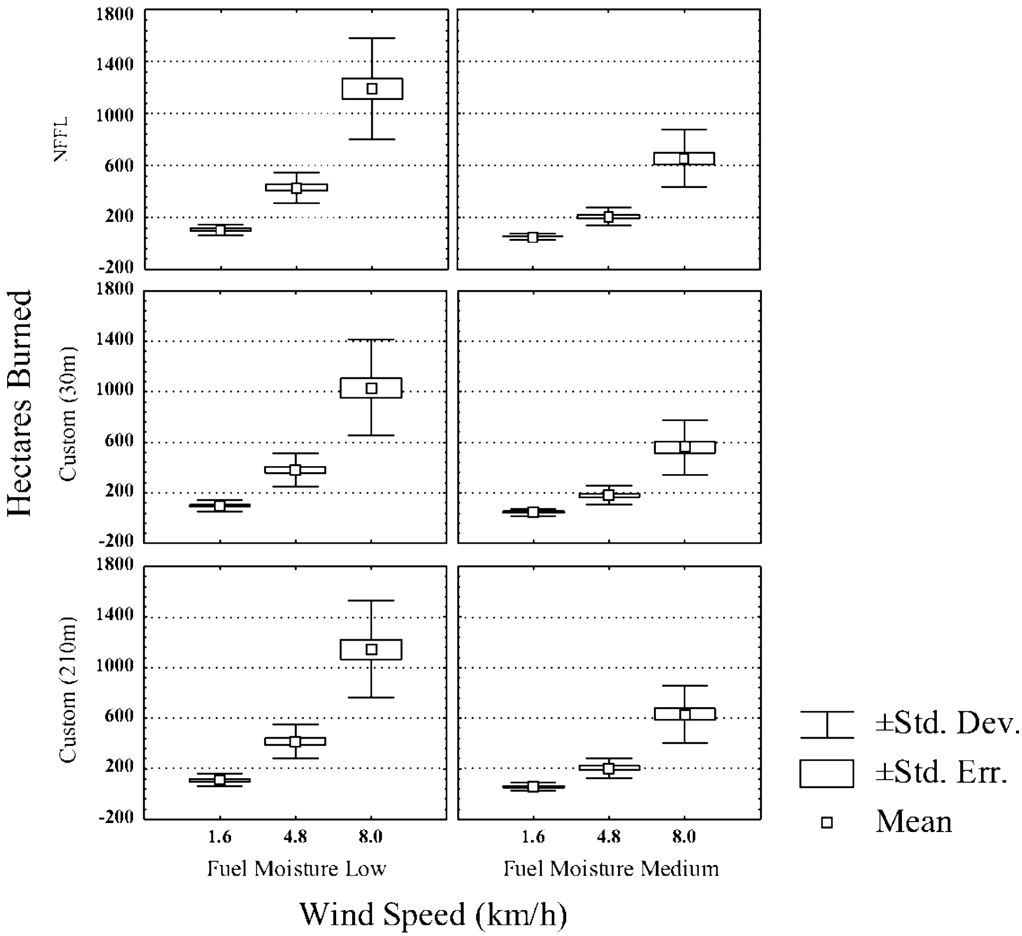

Fig. 5. Box-and-whisker plots sumarizing the average number of hectares burned in each simulation scenario.

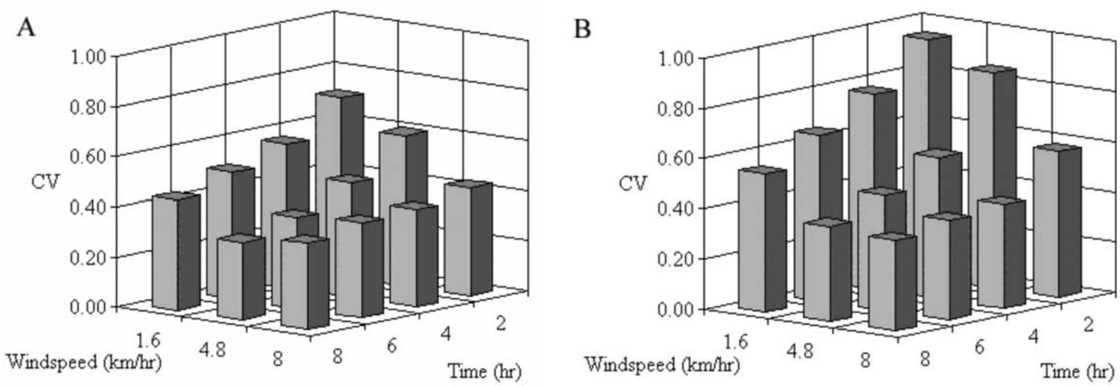

Fig. 6. Coefficient of variation for fires simulated using the custom high resolution fuels map: (a) low initial fuel moistures; (b) medium initial fuel moistures.

Table 5
Percent cover of each fuel model type in the 30, 210 m and NFFL fuels maps

Vegetation/fuel class	High resolution fuels map (30 m)	Medium resolution fuels map (210 m)	Low resolution fuels map (NFFL models)
Riparian Grass	4.0	3.4	4.0
Oak Woodland >30% cover	15.9	11.5	0.0
Dense Grass	2.1	0.9	0.0
Medium Grass	53.5	65.3	83.6
Sparse Grass	7.0	3.8	0.0
Grazed Grass	12.0	12.4	0.0
Shrubs	5.0	2.6	0.0
Bare Ground/ Buildings	0.5	0.1	12.4

The results of the Wilcoxon matched pairs test indicate that fire areas using the 30 m resolution map are significantly smaller than fire areas when using the 210 m resolution map for both low and medium fuel moistures (Table 6). This effect is probably due to the decreased areal extent in the 30 m resolution map of the Medium Grass fuel model leading to the increased extent of the Dense Grass, Sparse Grass, Shrubs, and Oak Woodland fuel models, and the Medium Grass fuel model having a higher spread rate (Tables 3 and 5). Wu et al. (1996) asserted that mapping fuels at high resolutions, therefore more accurately representing the spatial heterogeneity of fuels, reduces the uncertainty in simulation results. Our results confirm that assertion.

Simulated fire sizes using the NFFL fuel model map were all statistically different from those fires resulting from the custom fuel model map at 30 m resolution (Table 6). Predicted fire sizes using the NFFL fuels map and custom 210 m resolution fuels map were equivalent at low and medium wind speeds, however they were different at the highest wind speed. At low wind speeds the fire areas were small, and for small areas the NFFL fuel map and 210 m fuel map look alike (i.e. homogeneous). Also, the fuel model parameters used for the Medium Grass fuel model covering the largest area of the 210 m map were the same as NFFL fuel model 1. At the higher wind speeds the fire areas are larger and the fires area predicted using the NFFL map and 210 m map are statistically different. The custom fuels maps produced smaller predicted fire patterns due to the slower spread rates of the custom fuel models compared with NFFL fuel model 1.

4. Conclusions

The results of the Wilcoxon matched pairs test indicate that predicted fire areas using the 30 m resolution map are significantly smaller than when

Table 6
Wilcoxon test resulting p-levels

	Windspeed (km/h)		
	1.6	4.8	8
Low fuel moistures			
NFFL versus custom high	0.0079/R	0.0002/R	0.0000/R
NFFL versus custom low	0.5296/A	0.0455/R	0.0010/R
Custom high vs. custom low	0.0000/R	0.0000/A	0.0000/R
Medium fuel moistures			
NFFL versus custom high	0.0033/R	0.0003/R	0.0000/R
NFFL versus custom low	0.4074/A	0.5296/A	0.0004/R
Custom high versus custom low	0.0001/R	0.0000/R	0.0000/R

$\alpha = 0.05$, two-tailed test; A, accept H_0; R, reject H_0.

using the 210 m resolution map for both low and medium fuel moistures at all wind speeds (Table 6). The 30 m map better represents the actualspatial heterogeneity of the fuels as they occur on the landscape. Thus, if the fuel models are correctly formulated, the increased resolution of the 30 m map leads to an increased accuracy in predicted fire patterns and may result in better fire predictions. In the worst case for our study site, low fuel moistures and high wind speeds, the average fire size was about 15% larger with the 210 m map than the 30 m map (Fig. 5). The NFFL and custom fuels map at 210 m resolution produced statistically equivalent results at the low and medium wind speeds, but were significantly different at high wind speeds. When fire areas were sufficiently large due to higher wind speeds they were statistically different due to the more heterogeneous nature of the 210 m map. It appears that as the resolution of the map decreases and local areas look more like the generic fuels map, predicted fire results match those using the generic fuels map due to homogeneity and especially since the NFFL fuel model 1 accurately represented our study area.

These results suggest that site specific fuels data do increase the accuracy of predicted fires over generic fuels data. These conclusions might better be confirmed by choosing a study area that was much larger in size so that a greater number of map resolutions could be tested without fires expanding past the edge of the fuels map. The average fire size predicted using the NFFL fuels map was, at worst case, about 20% larger than the average predicted fire size using the 30 m custom fuels map. If the NFFL fuel model 1 parameters had not been used for the Medium Grass fuel model, differences between the predicted fires using the NFFL fuels map and those using the site specific fuel models may have been larger. The differences in predicted fire sizes between finely and coarsely mapped fuels may be larger or smaller for other landscapes depending on whether site specific fuel models match the NFFL fuel models. Since some site specific fuel models may have higher spread rates than NFFL fuel models, finely mapped fuels could produce predicted fire areas larger than those produced by NFFL models.

The results from this study suggest that the most appropriate scale at which to map fuels would be one that characterizes the fuels to the finest spatial scale reflecting the heterogeneity of the fuels. The most significant amount of effort in mapping fuels is in field sampling fuels and developing training and verification sites for image classification. The size and number of sample sites required to characterize the fuel types accurately for each landscape should remain constant regardless of the mapping resolution. The number of training and verification sites required is related to the size of the study area, i.e. larger areas require more sample sites because of the increased spatial extent for training and accuracy assessment. Assuming the number of fuel types remains constant, the cost of increasing map detail should be influenced only by the size of the area mapped. Since extensive sampling at these training and verification sites is not required the increased cost per sample site is small.

Land managers should assess whether the cost of detailed fuels mapping is justified for each application. If fuel loads are closely represented by NFFL fuel models then detailed mapping may not be required. Small errors in fuel model parameters may not be significant for small study areas. However, for large study areas, small errors could accumulate over the duration of the fire simulation leading to large errors in predicted fire sizes. If site specific fuel models are created then fuels should be mapped at the scale of heterogeneity that they occur on the landscape.

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