



A comparison of geospatially modeled fire behavior and fire management utility of three data sources in the southeastern United States [☆]

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ABSTRACT

Landscape-scale fire behavior analyses are important to inform decisions on resource management projects that meet land management objectives and protect values from adverse consequences of fire. Deterministic and probabilistic geospatial fire behavior analyses are conducted with various modeling systems including FARSITE, FlamMap, FSPro, and Large Fire Simulation System. The fundamental fire intensity algorithms in these systems require surface fire behavior fuel models and canopy cover to model surface fire behavior. Canopy base height, stand height, and canopy bulk density are required in addition to surface fire behavior fuel models and canopy cover to model crown fire activity. Several surface fuel and canopy classification efforts have used various remote sensing and ecological relationships as core methods to develop the spatial layers. All of these methods depend upon consistent and temporally constant interpretations of crown attributes and their ecological conditions to estimate surface fuel conditions.

This study evaluates modeled fire behavior for an 80,000 ha tract of land in the Atlantic Coastal Plain of the southeastern US using three different data sources. The Fuel Characteristic Classification System (FCCS) was used to build fuelbeds from intensive field sampling of 629 plots. Custom fire behavior fuel models were derived from these fuelbeds. LANDFIRE developed surface fire behavior fuel models and canopy attributes for the US using satellite imagery informed by field data. The Southern Wildfire Risk Assessment (SWRA) developed surface fire behavior fuel models and canopy cover for the southeastern US using satellite imagery.

Differences in modeled fire behavior, data development, and data utility are summarized to assist in determining which data source may be most applicable for various land management activities and required analyses. Characterizing fire behavior under different fuel relationships provides insights for natural ecological processes, management strategies for fire mitigation, and positive and negative features of different modeling systems. A comparison of flame length, rate of spread, crown fire activity, and burn probabilities modeled with FlamMap shows some similar patterns across the landscape from all three data sources, but there are potentially important differences. All data sources showed an expected range of fire behavior. Average flame lengths ranged between 1 and 1.4 m. Rate of spread varied the greatest with a range of 2.4–5.7 m min^{−1}. Passive crown fire was predicted for 5% of the study area using FCCS and LANDFIRE while passive crown fire was not predicted using SWRA data. No active crown fire was predicted regardless of the data source. Burn probability patterns across the landscape were similar but probability was highest using SWRA and lowest using FCCS.

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1. Introduction

Federal and state land management agencies with fire programs strive to plan fuels treatments and wildland fire response based on best available fire behavior science. Numerous systems have been developed to model fire behavior for a point or landscape to determine ecological effects and risk to resources, vegetation,

infrastructure, personnel, and communities (Peterson et al., 2007). Point fire behavior analyses often rely on specific data collected within a defined plot using established protocols. For a broader perspective, geospatial fire behavior analyses can be completed for an entire landscape of interest. A landscape includes multiple interacting ecosystems composing a heterogeneous land area (Forman and Godron, 1986). In this case, the landscape is defined as the study area and is equivalent to the administrative boundary.

Standard systems used in the United States to model geospatial fire behavior include FARSITE, FlamMap, FSPro (Fire Spread Probability), and Large Fire Simulation System. While these systems provide the ability to model fire behavior across a landscape, they do not provide the means to track vegetation and fuels trends at the scale of a stand or plot. Conversely, systems that rely on plot data do not readily allow for spatial fire behavior analyses without imputing plot data to the stand and landscape.

The Fuel Characteristic Classification System (FCCS) provides the ability to build custom fuelbeds including detailed vegetation and fuels structure and species composition based on each fuelbed component (Ottmar et al., 2007). The FCCS was designed to be inclusive of all fuelbed categories including canopy, shrubs, non-woody fuels, woody fuels, litter-lichen-moss, and ground fuels stratum (Ottmar et al., 2007). The FCCS uses a reformulation of Rothermel's (1972) surface fire spread model to calculate surface fire behavior including reaction intensity, flame length, and rate of spread (Sandberg et al., 2007a), crown fire (Schaaf et al., 2007), and fire potential ratings scaled on an index from 0 to 9 (Sandberg et al., 2007b). The FCCS has been used for point fire behavior analyses and to explore fire effects, carbon assessments, and wildfire smoke emissions (Sandberg et al., 2007; Ottmar et al., 2012). This system provides detailed plot-based vegetation and fuels inventory data which must be transformed to spatial data to perform geospatial fire behavior modeling using available programs such as FlamMap and FARSITE.

Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) is a multi-agency effort that provides consistent vegetation and fuels data across all land ownerships for the US at a resolution of 30 m (Reeves et al., 2009; Rollins, 2009). The data were derived from Landsat Enhanced Thematic Mapper and Thematic Mapper satellite imagery acquired from 1999 to 2003 and informed by field data (Reeves et al., 2009). LANDFIRE data include all fields and layers requisite for spatial fire behavior modeling (Rollins, 2009). In addition, LANDFIRE includes numerous spatial vegetation classifications based on existing and potential vegetation and fire regimes.

The Southern Group of State Foresters along with cooperators from federal and state agencies responded to the need for seamless data to evaluate fire potential and related values for the southern portion of the US by creating the Southern Wildfire Risk Assessment (SWRA). SWRA data include canopy cover and surface fire behavior fuel models derived from vegetation data developed during the US Geological Survey Gap Analysis Program which relied on 30 m satellite imagery acquired in the early 1990s from Landsat Thematic Mapper (Buckley et al., 2006). Additional SWRA data include community risk rating and an index that measures wildfire risk. SWRA lacks canopy data required by the fire behavior systems to model crown fire activity. Unless canopy data are provided from another source, the systems use one value for each canopy attribute across the entire landscape.

This paper compares modeled fire behavior from FlamMap using these three data sources and compares various characteristics of systems that may help managers determine which may be most effective to address land management objectives.

2. Methods

2.1. Study site

The Southern Atlantic Coastal Plain encompasses the area between the Atlantic Ocean and the Piedmont Plateau in the southeastern US. The study area is approximately 80,000 ha and lies along the Savannah River in South Carolina. Dominant vegetation types include loblolly pine (*Pinus taeda* L.), longleaf pine (*Pinus palustris* P. Mill.), hardwoods, slash pine (*Pinus elliottii* Engelm.), hardwood/pine mix, and baldcypress–water tupelo (*Taxodium distichum* (L.) Rich.–*Nyssa aquatica* L.) forests of various age and size classes. Elevation ranges from 19 to 150 m above sea level with maximum slopes of 28%. The area has a rich history of farming, grazing, and timber extraction (White and Gaines, 2000). Many of the forested stands are less than 60 years old. Current management focuses on forest products, conservation of flora and fauna, fire as an ecological process, and human safety. Fourteen fires occur on average per year in the study area with the vast majority of these fires being less than 5 ha (USDA Forest Service, 2009). Approximately 30% are caused by lightning and 70% are caused by humans (USDA Forest Service, 2009). Due to the flat terrain, fire spread is primarily a factor of available fuels, moisture, and wind.

2.2. FlamMap

FlamMap is a spatial fire behavior model that burns an entire landscape of interest using fuel moistures that are fixed or conditioned by wind and weather streams as well as winds that utilize either spatial wind grids or fixed speed and direction (Finney, 2006). FlamMap was utilized in order to provide a comparison of fire behavior including flame length, rate of spread, crown fire activity, and burn probabilities between the data sources. FlamMap provides both deterministic and probabilistic fire behavior results and therefore was determined to satisfy the study area objectives.

Eight input themes are required to model surface fire, crown fire, and burn probabilities. Topographical themes include slope, aspect, and elevation. Canopy data themes include canopy cover, canopy bulk density, canopy base height, and stand height; the final theme is surface fire behavior fuel models (FBFM). Landscape files for use in FlamMap were developed using these themes. Topographic themes were developed from Digital Elevation Model (DEM) data while canopy and FBFM data were developed from each of the three data sources. The extent for all simulations included a buffer around the study site boundary to minimize the edge-effects from random ignitions while computing burn probabilities; all outputs were clipped to the study area boundary once simulations were complete.

FlamMap supports the 40 FBFM described by Scott and Burgan (2005) and the 13 FBFM described by Anderson (1982) as well as custom fuel models developed by the user. Local data were used to refine accuracy of FBFM for all data sources to ensure that non-burnable areas were consistent between the data sources. Developed areas were reclassified as FBFM 91, water bodies including lakes and rivers were reclassified as FBFM 98, all non-burnable roads were reclassified as FBFM 99, and 2-track roads consisting of grassy medians were reclassified as FBFM 101 (refer to Scott and Burgan, 2005 for descriptions).

Fuel moisture values, wind speed, and wind direction were kept constant for all simulations to provide a comparison between the modeled data. The fuel moisture file specifies fuel moisture values for 1-, 10-, and 100-h timelag fuels, live herbaceous, and live woody fuels. Analysis of historic recorded weather data from the Savannah River Remote Automated Weather Station (RAWS) was completed using FireFamilyPlus (Bradshaw and Tirmenstein, in

preparation). Data were analyzed for the spring fire season to determine wind and fuel moisture ranges that support fire and roughly correspond to the 80th and 97th percentile weather for the period from February 20 to April 20, 1993 through 2009. This paper focuses on results using 5%, 7%, 12%, 60%, and 110% for 1-, 10-, 100-h, live herbaceous, and live woody fuels, respectively, and twenty-foot wind speeds of 48 km h^{-1} out of the southwest.

FlamMap calculates burn probabilities by simulating fire growth for a number of randomly located ignitions for a specified period of time. The ratio of fires burning a pixel to the total number of fires simulated computes the burn probability. For this analysis, burn probabilities were based on 2000 ignitions for 720 min per simulation. For processing efficiency, output resolution of 90 m was selected.

2.3. FCCS

The FCCS includes inventoried and synthesized fuelbeds; this study is based on custom fuelbeds created from inventoried plot data and explores the applicability and utility of using plot data at the landscape-scale. Custom fuelbeds were developed for the study area based on intensive field sampling of 629 plots located in 6239 delineated stands in the study site (Andreu et al., 2012). Regression relationships were developed from the plot fuel loadings and imputed to the stand polygon layer using stochastic prediction (Parresol and Blake, 2012). Cluster analysis was then conducted using the fire behavior for each stand as calculated within FCCS (Parresol et al., 2012). Seven custom FBFM were created from stands closest to the centroid of each cluster analysis and were used to populate the spatial landscape data. Landscape layers for the four canopy themes were developed using the canopy data calculated for each stand. As the FCCS data were only available for the study area, LANDFIRE data augmented the area within the analysis boundary that was outside the study site boundary.

2.4. LANDFIRE

LANDFIRE National version data were accessed using the LANDFIRE Data Access Tool, an interface tool functional in ArcMap. All eight themes necessary for analyses in FlamMap were downloaded. The 40 FBFM were utilized for all simulations.

2.5. SWRA

SWRA utilizes the 13 FBFM plus four custom non-burnable fuel models to represent water, developed areas, agricultural areas, and barren areas. Canopy cover was categorized into five classes. Since SWRA lacks canopy data other than canopy cover, SWRA data were paired with canopy data from LANDFIRE to complete FlamMap analyses.

3. Results and discussion

3.1. FlamMap results

Mean flame lengths ranged between 1 and 1.4 m (Figs. 1 and 2). SWRA had the lowest mean flame length while LANDFIRE had the highest mean flame length. It is interesting to note that the maximum flame length for SWRA was 7.8 m while LANDFIRE and FCCS both had maximum flame lengths above 26 m. Mean rate of spread ranged between 2.4 and 5.7 m min^{-1} (Figs. 1 and 3). FCCS had the lowest mean rate of spread while SWRA had the highest mean. The maximum rate of spread for FCCS data was 30.5 m min^{-1} whereas LANDFIRE and SWRA both had maximum rates of spread greater

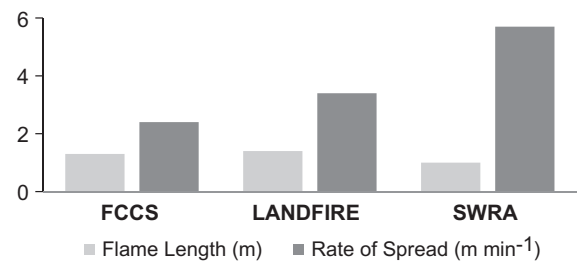


Fig. 1. Average flame lengths and rates of spread for the three data sources.

than 132 m min^{-1} . About 5% of the study area was categorized as passive crown fire with FCCS and LANDFIRE data while SWRA produced no passive crown fire; active crown fire was not predicted on the landscape regardless of data source. Burn probability for FCCS ranged to a maximum of 0.0055, LANDFIRE had a maximum burn probability of 0.009, and SWRA ranged up to 0.0105 (Fig. 4).

3.2. Modeled fire behavior

On average, modeled flame length and crown fire activity show little difference between the data sources while the average rate of spread shows the greatest variation. However, the differences in maximum flame length and rate of spread may indicate important differences when assessed locally and may be used to define areas where treatment may be desired to mitigate fire potential and fire effects. Burn probability is related to the distribution of fire size which is related to the rates of spread and the fuel continuity. The relatively low probabilities suggest that fire spread is limited on this landscape which is consistent with actual fire sizes historically observed. For management purposes, burn probabilities are most suited for identifying high probability areas to evaluate where management actions may be most effective in achieving resource and protection objectives.

Some of the differences in modeled fire behavior between the data sources can be attributed to the proportions of grass and shrub fuel types that are represented in each dataset and the dynamic herbaceous moisture content of the 40 FBFM from LANDFIRE. The live herbaceous load transfers to dead depending on the herbaceous moisture content in a dynamic FBFM (Scott and Burgan, 2005). This allows the time of year to be factored in based on the level of curing in the herbaceous fuels. The variations in fire behavior demonstrate the differences in the underlying data and indicate the need to carefully evaluate data for accuracy. Additionally, data performance should be evaluated by comparing modeled fire behavior to observed fire behavior.

3.3. Utility of data

Geospatial fire behavior systems have gained momentum in the last decade as they allow for landscape fire behavior analyses, support the strategic placement of fuels treatments, forecast burn probabilities, and are useful during wildfire incidents to deterministically and probabilistically project fire growth. To support geospatial fire behavior systems, several efforts have produced readily available data themes with state, regional, and national extents. Alternatively, local plot data can be used for analyses. The inherent usability of data for geospatial analyses varies. While many of the readily available data sources provide a valuable means for geospatial fire behavior analyses they do not provide sufficient detail for a stand or plot as they lack site-specific measured data.

The key to choosing the proper data source lies in asking and answering questions at the outset. Specific management objectives

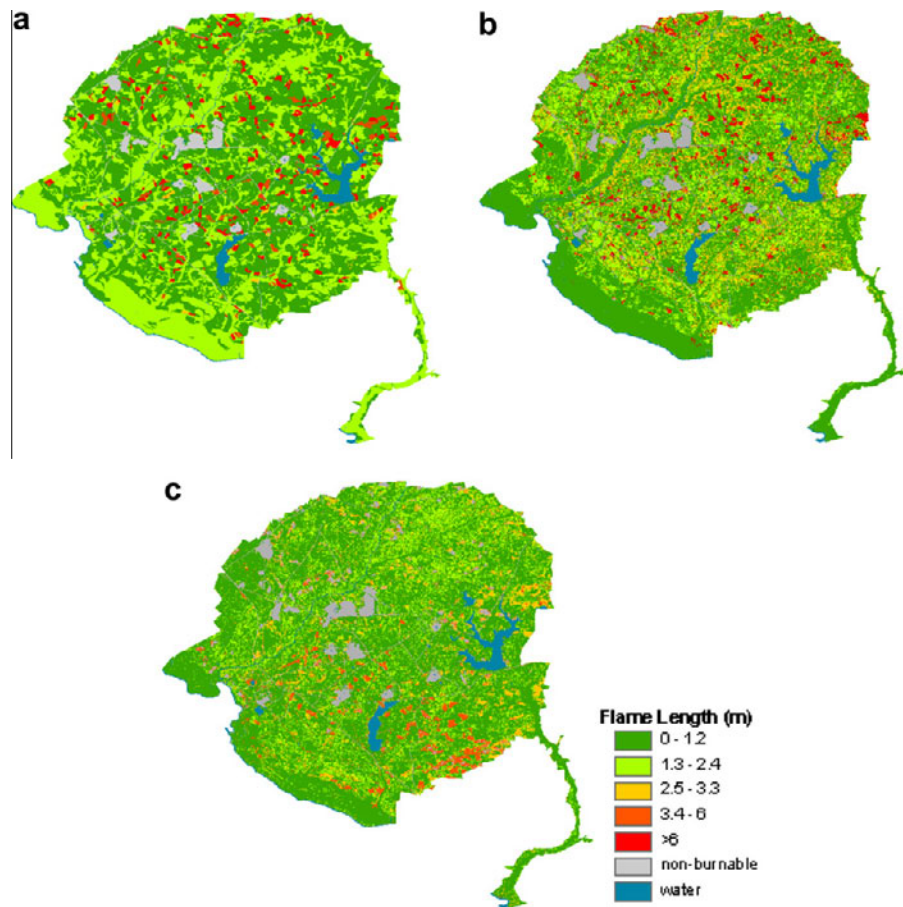


Fig. 2. Comparison of flame lengths for the study area using three data sources, (a) Fuel Characteristic Classification System, (b) LANDFIRE, and (c) Southern Wildfire Risk Assessment.

should be identified during this process. Important considerations when choosing data may include: data availability, data accuracy, project scale, site-specific inventory and monitoring, fire behavior analyses, values at risk analyses, and the ability to quantify fire effects (Table 1).

If the objective is to provide spatial data at no cost to the user, either LANDFIRE or SWRA may be valid choices. Both are easily available via the internet for the conterminous southeast US and include a myriad of different vegetation and fuels data. LANDFIRE and SWRA offer seamless data available for the southeastern US across all land ownerships. Plot data, such as the FCCS fuel strata or Forest Inventory Analysis (FIA), take more time to collect, require statistical analyses to assign attributes across a landscape, and require additional geographic information system (GIS) and custom fuel model expertise in order to develop data for geospatial fire behavior analyses.

Concerning data accuracy, scale is tantamount. Data accuracy can be high for small projects where data can be collected at a relatively fine resolution. As the geographic scope of a project increases, it becomes more difficult to retain accuracy at a fine resolution. Usually data is limited, assumptions must be made to apply the data across a broad area, and data resolution becomes much coarser. The FCCS data collected for each plot are expected to be quite accurate; however, once the data are imputed to the stand it seems logical that accuracy would decrease. LANDFIRE and SWRA both utilize satellite imagery. LANDFIRE data were informed by available plot data and both data sources used local professional expertise to improve accuracy on a regional, but not local, scale. Accuracy is difficult to assess at a generalized broad scale and

should best be evaluated by the local user. An important component to remember is that accuracy may be improved by calibrating data (Stratton, 2009) which can heighten usability at the local scale. Because data accuracy can be improved at the local scale, this should not be the key driver when choosing a data source.

The geographic scope of the project is important in determining data sources. Assessing fire behavior for a small project such as a prescribed fire, wildfire incident, or fuels treatment in a watershed requires the finest resolution and most accurate data available. Results of such analyses are often used to make tactical decisions that are important to achieve management objectives, particularly human safety. FCCS and FIA or other plot data provide the best accuracy and resolution. However, if a project encompasses a large geographic area, coarser resolution and lower accuracy may not only be acceptable but be required because it is the best data available. Analyses at this scale should be used primarily for strategic decisions. LANDFIRE and SWRA at 30 m resolution work well for larger scale analyses. However, as projects get larger, data may need to be aggregated to a coarser resolution due to computer processing capabilities. While fire behavior characteristics and a single fire spread prediction can be readily calculated at 30 m resolution, probabilistic models usually require a coarser resolution for most landscapes. Aggregating the data introduces additional inaccuracies, making interpretation and application at a project-scale difficult.

If the overriding objective is to provide a baseline inventory and allow for subsequent monitoring of all aspects of the fuels profile, a basis for effectiveness monitoring, or data for detailed fire effects analyses the FCCS may be the best option. Plot data allow for

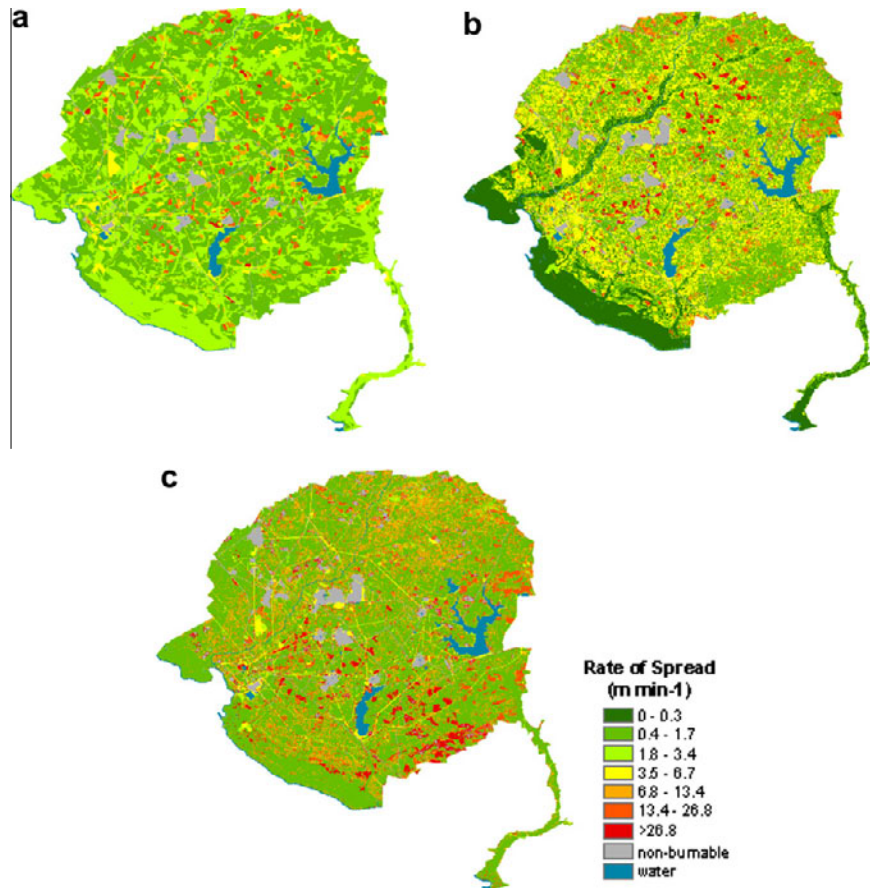


Fig. 3. Comparison of rates of spread for the study area using three data sources, (a) Fuel Characteristic Classification System, (b) LANDFIRE, and (c) Southern Wildfire Risk Assessment.

detailed statistical analyses and provide the ability to track trends in vegetation and surface fuels over time or changes resulting from natural disturbances or management activities. This data may be useful to track certain types of habitat based on canopy characteristics or surface fuel loading.

If the objective is to perform spatial fire behavior modeling, LANDFIRE may be the best option although it could certainly be argued that SWRA and LANDFIRE data could be combined to satisfy this objective. At this point it may be suitable to consider data accuracy and choose the most appropriate source for the analysis area. The FCCS data involved a prolonged process to yield spatial data from plot data; the necessary skills are often not locally available. Geospatial data are often used by incident management teams to provide consistent data during wildfires and the ability to perform spatial fire behavior analyses and calculate burn probabilities. The FCCS plot data would not allow for this use on incidents, but would still allow for point-based fire behavior analyses. While point-based analyses allow for assessment of site-specific changes in fire behavior before and after treatments, they may not be used to assess changes in fire spread across a landscape.

Analyzing threats from wildfire to values remains a viable concern in the southeastern US. The ability to prioritize areas that have the greatest risk can be helpful to local managers during a fire incident. Likewise, having the opportunity to complete multiple iterations representing potential treatments allows for informed decisions. The community risk rating data and wildfire risk index in SWRA provide the ability for local managers to analyze values potentially at risk from fire.

Quantifying fire effects can be very important to managers in order to determine whether prescribed fire objectives were successfully met, to maintain a treatment history that can be consulted in comparable vegetation types, and to have an accurate record of the existing condition of vegetation all of which can be accomplished using plot data such as the FCCS. In addition, this effort can include effects to other resources including wildlife habitat, soils, and hydrology. Prescribed fire objectives often include goals for reducing surface fuel loadings; comparison of pre- versus post-fire loadings can be quantitatively summarized using plot data. Analyzing effects following wildfires may help determine if a particular fire was within an acceptable range of variability considering management objectives, help determine reforestation needs to comply with applicable laws and policies, and track successional stages of vegetation. If a wildfire occurs in an area with plot data, remeasuring following the incident would be straightforward.

Validating the modeled fire behavior results by comparing the values to observed fire behavior is a critical next step. Actual fire observations may indicate how predicted fire behavior deviates from observed fire behavior. Observed patterns may allow formulation of general rules to apply to landscape data layers in order to increase reliability of modeled data. For example, more crown fire may be observed than has been predicted for specific weather conditions. Applying an adjustment factor to the layer that affects crown fire initiation (canopy base height) may adequately resolve the differences; thus establishing an adjustment factor that can be used broadly in order to obtain more accurate predicted fire behavior. Observed fire behavior may also indicate patterns for changing

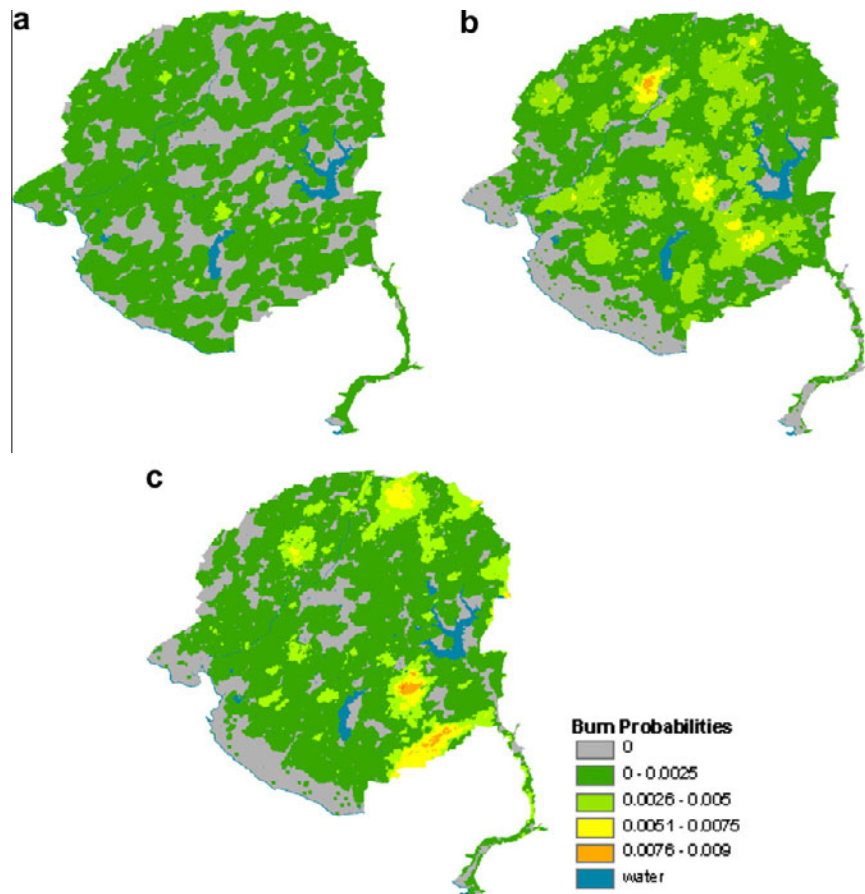


Fig. 4. Comparison of burn probabilities for the study area using three data sources, (a) Fuel Characteristic Classification System, (b) LANDFIRE, and (c) Southern Wildfire Risk Assessment.

Table 1
Potential utility of the three different data sources.

	FCCS	LANDFIRE	SWRA
<i>General</i>			
Data source	Plot	Satellite	Satellite
Resolution	Plot (imputed to stand)	30 m	30 m
Geographic scale and extent	Local study site	Complete national	Complete southeast
<i>Inventory</i>			
Canopy data	Plot (imputed to stand)	Complete	Canopy cover only
Comprehensive fuels inventory	Yes	No	No
Relationship – fuel model and canopy	Dependent	Independent	Independent
Surface fuel models	Custom	FBFM13, FBFM40	FBFM13
<i>Utility</i>			
Smoke emissions	Complete	Limited	Very limited
Carbon analysis	Complete	Limited	Very limited
Incident management	Limited	Complete	Moderate
Fuel treatment changes	Surface fuels and canopy data	Canopy data	Canopy cover
Quantify prescribed fire effects	Complete	Limited	Limited
Quantify wildfire effects	Complete	Limited	Very limited
<i>Data Collection</i>			
Field verification	Data/subjective	Subjective	Subjective
Costs	High for plot collection and conversion to custom FBFM	Low	Low

FBFM in the data. With sufficient historic fire behavior and progression information, landscape data can be modified and calibrated prior to an incident or planning needs. However, if there is little available fire history, such modifications and calibration may need to occur during the incident or project implementation.

Calibrated data will improve the accuracy of geospatially modeled fire behavior and subsequent utility for planning and incident

management. Modeled fire behavior that closely reflects observed behavior can be extremely important, particularly during planning, for evaluating potential fire effects to species that have tolerance thresholds. For example, underpredicting fire behavior may result in unintended ponderosa pine mortality following a prescribed fire. Accurate fire behavior modeling is especially important in incident management where decisions regarding human safety often hinge

on predicted fire behavior, particularly flame length and rate of spread. Burn probabilities are useful in planning and may change with calibrated data. If FBFM or canopy characteristics are significantly modified, the areas of highest burn probability may be different than with uncalibrated data. If only minor or localized changes to the landscape layers are necessary, calculated probabilities may slightly differ but the relative location of highest and lowest burn probability is likely to vary little.

Statistical analyses can be applied to determine which data provide the best overall accuracy or may be most applicable for particular management situations. Conducting similar comparisons in ecosystems with more frequent fire and documented fire behavior will also help in establishing relationships between available data. The methodologies utilized for this project and data utility are applicable to a broader scale than the southeast US as these are issues and decisions faced by many natural resource managers. California has statewide fuels data and the US Northern Rockies has detailed spatial vegetation data available for land administered by the USDA Forest Service. Both experience frequent fires and provide opportunities for similar comparisons.

4. Conclusions

Multiple data sources are available for use with various fire behavior modeling systems. No one data source provides the utility or accuracy for a diverse fire management program. Selection of a data source to complete analyses for land management activities depends on the requisite scale of analysis and necessary resolution. Predicted fire behavior from the various data sources may have important differences and should be evaluated based on objectives. Most geospatial data for fire modeling has been developed to adapt to the requirements, limitations, and assumptions of existing fire behavior modeling systems. SWRA and LANDFIRE data provide spatial data that can be used for fire growth modeling; however, the accuracy may limit the utility for an individual project. FCCS is a relatively new system that attempts to overcome some previously imposed limits; however, it currently does not provide geospatial data to analyze potential fire progression or analyze burn probabilities without imputing plot data to the stand. Areas subject to frequent disturbance or rapid succession will require regular evaluation and modification to ensure data reflects field conditions. Some data sources have regular maintenance schedules while others may require manual updates from the user.

While all data sources have utility, each fits a different niche and determination of the best fit depends on the particular management objectives in question. The most critical step in choosing the best data and appropriate analyses is clearly defining the metrics that will determine if the management objectives are achievable or have been achieved. On-going research is being conducted to better understand various aspects of fire behavior, particularly crown fire. As this research becomes integrated, more detailed data may provide better analyses and broader utility for multiple objectives.

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