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LANDFIRE – A national vegetation/fuels data base for use in fuels treatment, restoration, and suppression planning

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ABSTRACT

LANDFIRE is the working name given to the Landscape Fire and Resource Management Planning Tools Project (http://www.landfire.gov). The project was initiated in response to mega-fires and the need for managers to have consistent, wall-to-wall (i.e., all wildlands regardless of agency/ownership), geospatial data, on vegetation, fuels, and terrain to support use of fire behavior and effects prediction systems in guiding policy and management decisions. Base layers were created in a 5-year program of research and development ending in 2009, with processes in place to periodically update fuel and vegetation layers in response to anthropogenic and natural disturbances. LANDFIRE has been institutionalized as the primary data source for modeling activities aimed at meeting the goals of the United States' National Cohesive Wildland Fire Management Strategy, and the data are available on-line to any user for conducting landscape analyses. Data access and use are high and expected to grow with the increasing scope and complexity of wildland fire management, thus requiring continued LANDFIRE improvements and updates.

1. Introduction

The term mega-fire has emerged in recent years to draw a distinction between serious historic wildland fires and the increasingly common fires of historically unprecedented magnitude in their impact on people in terms of either loss, suppression costs or both (Williams et al., 2011; North American Forestry Commission, 2012). Mega-fires are a new, rather than cyclic phenomenon (Roose and Swetnam, 2012) and are likely to become more common (Moritz et al., 2012).

Mega-fires are impressive in sheer spatial scale and impacts on people, with potentially devastating impacts on health, lives, property, infrastructure, natural and cultural resources, and ecosystem services such as clean air, water and esthetics. The recent increase in the scope and complexity of wildland fire management is attributable to three factors: recent climate trends, the influx of homes and infrastructure into wildlands, and land management practices that have contributed to the increasing mass and continuity of hazardous fuels (Keane et al., 2002a; Radeloff et al., 2005; Karl et al., 2009; Roose and Swetnam, 2012; Stephens et al., 2012). Humans rely on vegetation and climate for their existence and must learn to adapt to wildland fire.

Given their complexity, mega-fires are a not solely a fire management problem, they are a societal problem. Joint efforts of many segments of society are required to significantly affect the mega-fire trend. Climate, vegetation, fire and humans are dynamically coupled. Changes in one affect the others in multiple ways (Fig. 1) (Ryan, 1991; Millar et al., 2007; Bonan, 2008; Moritz et al., 2012). Although there are regional exceptions, in most of the world humans are the dominant source of ignitions and increasingly so. Humans directly impact climate, vegetation, and fire through land-use changes including intentional ignition of fires. In addition to land-use changes, natural fires, principally from lightning, unintentional human ignitions, fire suppression and vegetation succession also alter land cover. All land cover changes affect the climate system by altering water and energy budgets and atmospheric fluxes. In addition fires directly affect the climate system through production of a variety of greenhouse gas emissions. Future fire potential and the risk of loss of natural resources and socio-economic values vary with changes in land cover and building of human infrastructure within the wildland environment (Calkin et al., 2010). Climate-driven vegetation stress and unfavorable fire weather increases fire potential and fire-induced losses. Mega-fires cross political boundaries affecting multiple jurisdictions requiring coordinated intra- and inter-governmental responses. Globally, governments are mobilizing to deal with the increasing wildfire threat. The United States government, in response to the mega-fire problem, has implemented a series of laws and policies which spurred development of decision support tools

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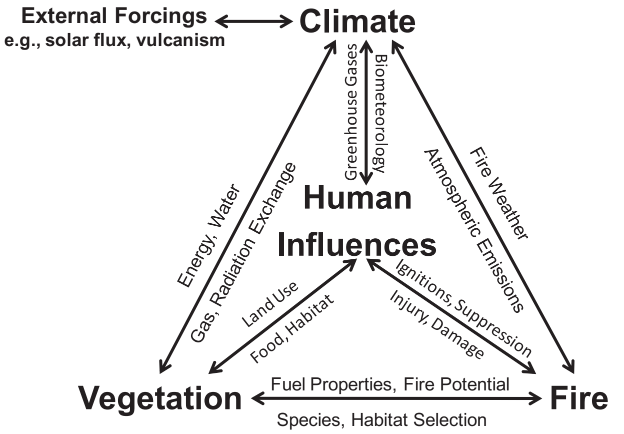

Fig. 1. Human activities affect the dynamic coupling between climate, vegetation, and fire, and thereby alter the human experience. Adapted from Ryan (1991).

that standardize wildland fire risk analysis to improve the safety and effectiveness of all fire management activities. These efforts are bannered under the name "Cohesive Wildland Fire Management Strategy" (http://www.forestsandrangelands.gov/strategy/documents/reports/1_CohesiveStrategy03172011.pdf). One of the basic premises of the Cohesive Strategy is that restoring resilient landscapes will ultimately result in reduced personal injury, property and resource damage, and suppression costs. To that end, one major component of the "Strategy" has been to develop the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) (http://landfire.gov, visited 6-26-2012). LANDFIRE allows any geographical information system (GIS) user to download up to 24 data layers describing fuels, vegetation, and terrain critical for predicting fire behavior and effects. This paper describes the U.S. fire situation that led to development of LANDFIRE, the various LANDFIRE applications in use today, and the future of LANDFIRE in an effort to continue reducing costs and losses from wildland fires.

2. Background

The 1987 and 1988 fire seasons ushered in a new age in wildland fire management in the United States. Between the early 1900s and 1970 the area burned in the United States followed a downward trend, reversing around 1975 (Littell et al., 2009) with a major upswing in the mid-80s. Between August 30 and September 3, 1987 lightning ignited 1600 fires in nine western states. Fires rapidly coalesced into major conflagrations and outstripped fire-fighting capacity, with the main center of activity in Northern California and Southern Oregon. That complex of fires became known as the "Siege of '87." By the time the fires were out in late November, approximately 265,000 ha had burned. The scene was repeated in 1988 when roughly 30,000 firefighters battled fires throughout the West, including the famous "Yellowstone Fires" that burned 640,000 ha from June through October (Guth and Cohen, 1991). By the time the 1988 fire season was over, two million hectares had burned, 10 firefighters had lost their lives, and the Federal Government had spent $584 million on suppression (USFA, http://www.usfa.fema.gov/downloads/pdf/statistics/v1i3-508.pdf, visited June 2012). Managers were forced to manage fires encompassing multiple jurisdictions on large landscapes for time periods spanning weeks to months (Bushey, 1989; Rothermel et al., 1994). Spatial and temporal data and decision support tools were inadequate to the task. Although the term was yet to be coined (Williams and Hamilton, 2005), the mega-fire era had arrived.

Coincident with the emergence of mega-fires the emergence of high speed computers and geospatial technologies provided new avenues for development of decision support tools. Research initiated under the US National Park Service's Global Change Program in Glacier National Park (Keane et al., 1997a; White et al., 1997) was developing vegetation, fuel, terrain, and weather/climate information for the purpose of understanding how fire regimes might change under varying future climate scenarios to develop a monitoring and modeling framework for global change assessment (Keane et al., 1997a). In 1994 lightning ignited a series of fires within the study area (Zimmerman et al., 2011), providing an opportunity to model fire behavior for actual fires to support managers' decisions on whether to allow fires to continue to burn naturally, or whether to suppress them (Finney and Ryan, 1995). Results indicated promise for real-time spatial modeling of wildland fire spread but identified the critical need for adequate spatial data on fuel properties and local winds.

1994 was a year of major fire activity throughout the West with 1.6 million hectares burning. Thirty-four fire fighters died in the line of duty including 14 in Colorado's South Canyon Fire (Butler et al., 1998). In response, a Federal Wildland Fire Management Policy and Program Review (USDI et al., 2001) was conducted, formulating nine guiding principles for fire management, affirming the role of fire as a natural process needing to be safely reintroduced, requiring that all burnable lands have fire management plans employing science-based risk management principles, and requiring interagency collaboration and standardization. The review directed agencies to manage fire as an interagency, landscape-scale process rather than a series of discrete events. Unfortunately, vegetation and fuels classification and mapping inconsistencies or a lack of data was problematic for agencies attempting to manage at a landscape level (Keane et al., 2001). This prompted scientists at the Missoula Fire Sciences Laboratory to embark on a series of studies on increasingly large landscapes to develop a scientific basis for mapping vegetation and fuels (Keane et al., 1997b, 1998a,b, 2002b; Menakis et al., 2000) to support fire management in the Selway-Bitterroot Wilderness Area of Idaho and Montana (ca. 95,000 ha) (Keane et al., 1998a), the Gila Wilderness Area of New Mexico (ca. 122,000 ha) (Keane et al., 2000a,b), and Southern Utah-Northern Arizona (ca. 6,100,000 ha) (Long et al., 2003; Stratton, 2004; Hood and Miller, 2007).

One of the major tenets of the 1995 Federal Fire Policy was that active fuels management and restoration would lead to reduced wildfire cost plus loss, but a US Government Accountability Office review of the US Forest Service's fuels management program concluded that the agency lacked a cohesive strategy for managing fuels to accomplish reductions in fire costs and losses. In response, a coarse-scale assessment of fire hazard and risk was conducted for the coterminous United States (Schmidt et al., 2002). This effort helped to identify areas where major problems existed but the data lacked sufficient spatial resolution and data quality to support fuel and wildland fire management. The fires of 2000 led to another revision of the Federal Fire Policy (USDI et al., 2001) and the creation of the National Fire Plan (Kostishack and Rana, 2002), further reaffirming the need for active fuels management, providing new funding to help solve the growing fire problem, and guiding development of a "10-Year Comprehensive Strategy – A Collaborative Approach for Reducing Wildland Fire Risks to Communities and the Environment." Improved safety, better landscape management and community-based fire management were focal points of the strategy. Under National Fire Plan funding the Missoula Fire Sciences Laboratory (FiSL), the USGS EROS Data Center, and The Nature Conservancy were tasked with developing a proof of concept for mapping fuels and vegetation in two pilot areas, one in Utah (69,907 km^2) and one in Idaho and Montana (117,976 km^2) and the LANDFIRE name was coined (Rollins and Frame, 2006). After

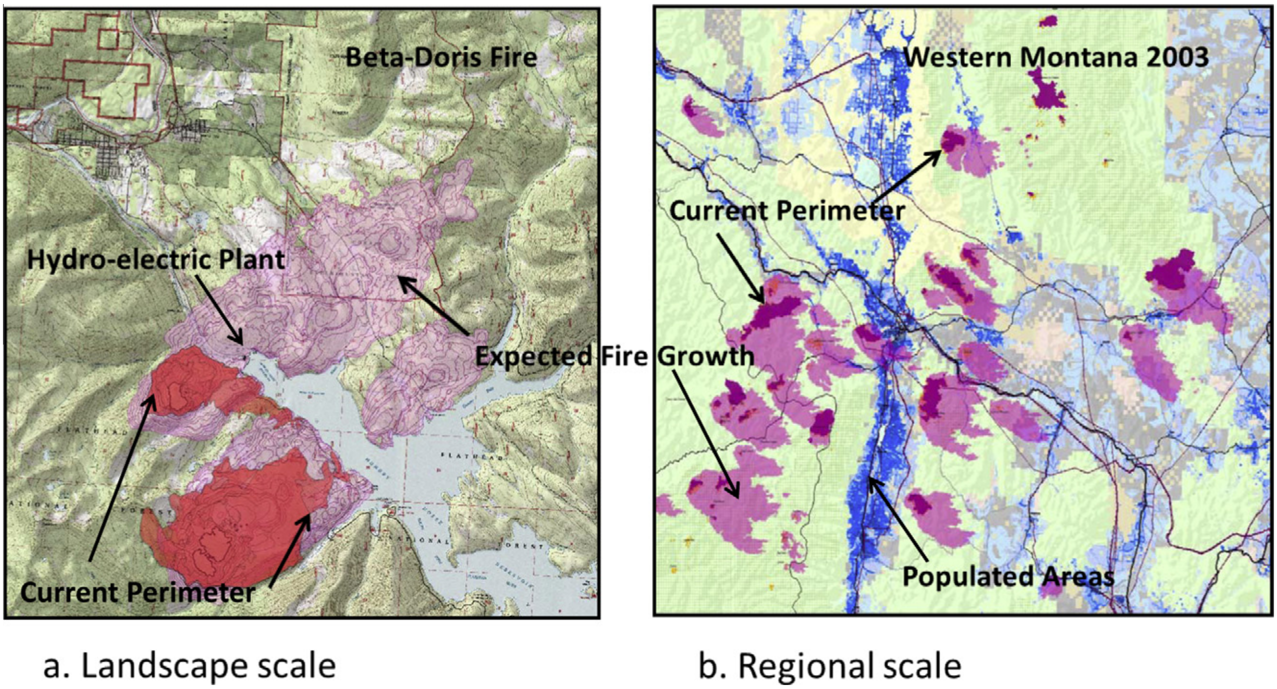

Fig. 2. FARSITE (Finney, 2004) projections of fire growth on a landscape with next day's weather forecast for the Beta-Doris Fire on the Flathead National Forest (a). Courtesy of Mark Finney. FARSITE projections of fire growth for several fires in western Montana (b) given anticipated high wind event. Courtesy of Jim Menakis.

another costly fire season in 2002 with the 187,000 ha, 43 million dollar Rodeo–Chediski fire in Arizona; the 201,000 ha, 150 million dollar, Biscuit fire in southern Oregon and northern California; and the 56,000 ha, 40 million dollar Hayman fire in Colorado, there was political traction to pass the Healthy Forest Restoration Act (P.L. 108–148) in 2003.

In 2003, as numerous fires burned in the Idaho-Montana pilot area burned, FiSL employees worked closely with emergency management teams and used data and models to assess potential fire spread for pending and possible weather for short-term tactical fire planning and long-range strategic planning (Fig. 2). This success led to the creation of the National Landfire Project. In May of 2004 the Wildland Fire Leadership Council, an inter-governmental committee of federal, state, tribal, county, and municipal government officials created by the Secretaries of Agriculture and Interior (http://www.forestsandrangelands.gov/leadership/index.shtml), directed the Project under a 5-year charter to develop the data and models to support fire policy and management. The goal of the Project was to develop objective, repeatable, and credible fuels and vegetation mapping procedures and create wall-to-wall GIS data layers for all wildlands (non-urban, non-croplands) across all ownerships/jurisdictions (Rollins and Frame, 2006; Reeves et al., 2009; Rollins, 2009; Vogelmann et al., 2011). One of the design criteria was to develop inputs to a suite of fire behavior and effects models to support fire management decision-making.

3. Creating LANDFIRE data

In the process of creating LANDFIRE the team of scientists acquired and rectified 57 existing GIS data layers including Landsat-TM images, soils, and terrain, and meteorology; modeled 22 biophysical gradients, and created 13 wildland fuels layers. They also compiled a field reference data base from over 800,000 agency and cooperator's vegetation inventories. Data are consistent for each 30-m^2 pixel in the coterminous US. Data availability required different procedures for Alaska and Hawaii, and not all data are available in those states. In addition to the biophysical data LANDFIRE also developed state-and transition (http://essa.com/tools/vddt/) Vegetation Dynamics Models (VDM) (http://www.landfire.gov/national_veg_models_op2.php) which can be used to model landscape change with and without disturbance as an aid to assessing change in fire potential over time. Detailed description of LANDFIRE data and procedures is beyond the scope of this paper and readers are referred to previously published papers (Rollins and Frame, 2006; Rollins, 2009; Reeves et al., 2009) and www.landfire.gov for complete descriptions of processes and variables (Table 1). LANDFIRE data are in the public domain and downloadable by anyone. In the 27 months prior to 2012 first-time visitors and total visits to the site have been steady, around 4000 and 20,000 visits per month, respectively (Eidenshink, 2012). The heaviest access has been dot-com organizations. Government access was steady at 1000–2000. The number of downloaded files has consistently been 80,000–120,000 files per month. While government and educational organizations are prominent users of the data, it is impossible to know how data are being applied within the wildland fire policy and management realm. Under the Healthy Forest Restoration Act and National Fire Plan land managers report those areas where management actions have modified fuels and fire regime condition class (FRCC, Schmidt et al., 2002, http://www.frcc.gov/, accessed June 2012; Barrett et al., 2011; NFPORS, https://www.nfpors.gov/, an internal agency reporting system). Significant fires are reported and analyzed to update spatial data layers through the Monitoring Trends in Burn Severity (MTBS, http://www.mtbs.gov, accessed June 2012; Eidenshink et al., 2007; Vogelmann et al., 2011). NFPORS and MTBS information are used to systematically update LANDFIRE data layers, thereby extending the "shelf-life" of the original LANDFIRE data products.

4. LANDFIRE applications

LANDFIRE data have many applications in supporting fire and land management planning. LANDFIRE provides users with Anderson-13 (Anderson, 1982) and Scott and Burgan-40 (Scott and Burgan, 2005) stylized fuel models that can be used as inputs

Table 1
Geospatial data products downloadable from LANDFIRE (http://www.landfire.gov).

Vegetation products	
Existing vegetation	Potential vegetation
Existing vegetation type – complexes of plant communities	Biophysical settings – vegetation that may have been dominant on the landscape pre Euro-American settlement
Existing vegetation cover – vertically projected percent cover of the live canopy layer for a specific area	Vegetation dynamics models – state-and-transition models representing pre-settlement reference conditions for each biophysical setting
Existing vegetation height – average height of the dominant vegetation	Environmental Site Potential – vegetation that could be supported at a given site based on the biophysical environment
Wildland fuel products	
Surface fuel	Canopy fuel
13 Anderson fire behavior fuel models – original 13 fire behavior fuel models, represents severe fire conditions (Anderson, 1982)	Forest canopy cover – proportion of the forest floor covered by the vertical projection of the tree crowns
40 Scott and Burgan fire behavior fuel models – fire behavior fuel model predictions beyond the severe fire season, such as prescribed fire and fire use applications (Scott and Burgan, 2005)	Forest canopy height – average height of the top of the vegetated canopy
Fuel characteristic classification system fuelbeds – provide land managers, regulators, and scientists with a nationally consistent and durable procedure for characterizing and classifying fuels (Ottmar et al., 2007)	Forest canopy bulk density – density of available canopy fuel in a stand
Fuel loading models – surface fuel classification system to characterize wildland surface fuel (Lutes et al., 2009)	Forest canopy base height – average height from the ground to a forest stand's canopy bottom
Canadian forest fire danger rating system – Canadian system for rating the risk of forest fires, distributed for Alaska only	
Topographic products	
Aspect – azimuth of the sloped surfaces across a landscape	
Elevation – land height (meters) above sea level	
Slope – % change of elevation over a specific area	
Ancillary fire planning products	
Historical fire frequency and severity	Vegetation departure
Fire regime groups – characterize the presumed historical fire regimes within landscapes	Vegetation condition class – a discrete metric that quantifies the amount that current vegetation has departed from the simulated historical vegetation reference conditions
Mean fire return interval – average period between fires under the presumed historical fire regime	Vegetation departure – range from 0 to 100 depicting the amount that current vegetation has departed from simulated historical vegetation reference conditions
% Low-severity fire – low-severity fires relative to mixed- and replacement-severity fires under the presumed historical fire regime	Succession Classes – current vegetation conditions with respect to vegetation species composition, cover, and height ranges of successional states occurring within each biophysical setting
% Mixed-severity fire – mixed-severity fires relative to low- and replacement-severity fires under the presumed historical fire regime	
% Replacement-severity fire – replacement-severity fires relative to low- and mixed-severity fires under the presumed historical fire regime	

Table 2
Fire behavior and effects models supported by LANDFIRE data.

Model	Source
FARSITE – Geospatial landscape fire behavior simulation model & WFDSS equivalent "Near Term Fire Behavior"	Finney (2004)
FlamMap – Geospatial landscape fire potential model and WFDSS equivalent "Short Term Fire Behavior"	Finney (2006)
Minimum Travel Time (MTT) – Calculate fastest fire spread paths across a landscape	Finney (2002)
FSPro – Geospatial Fire Spread Probability model	Finney et al. (2011a)
BehavePlus – Point-based fire behavior, environment, and effects modeling system	Andrews (2009)
Nexus – Point-based crownfire prediction model	Scott and Reinhardt (2001)
FOFEM – Point-based fire effects prediction system (fuel consumption, smoke production, tree mortality, soil heating)	Reinhardt (2007)
CONSUME – Point-based fire effects prediction system (fuel consumption)	Prichard et al. (2007)

Table 3
Example model applications for LANDFIRE data in varying fire behavior analyses.

	One fire	Many fires
One weather scenario	FARSITE, BehavePlus, Nexus, MTT	FlamMap
All weather scenarios	FSPro	FPA Large Fire Simulator

for predicting fire behavior with various software programs (Table 2). BehavePlus (Andrews, 2009) and Nexus (Scott and Reinhardt, 2001) are point-based, non-geospatial models used for conducting analyses such as when developing fuel treatment or restoration prescriptions. These models allow users to vary fuel moisture and weather parameters to game different treatment alternatives for a specific site of interest. Geospatial LANDFIRE grids can be used for short-term, mid-term and long-term fire behavior analyses in real-time or for planning fuels and restoration treatments (Table 3). The geospatial models include FlamMap (Finney, 2006) for short-term fire behavior, FARSITE (Finney, 2004) for mid-term fire behavior, and FSPro (Finney et al., 2011a) for long-term probabilistic fire spread. These tools can be used for landscape-level fire behavior assessments and fuel treatment optimization planning.

LANDFIRE is also utilized at programmatic levels, such as the Fire Program Analysis (FPA) System (http://www.fpa.nifc.gov/), which provides managers with a standard strategic planning and budgeting process to evaluate the effectiveness of alternative management strategies. The FPA Large Fire Simulator uses LANDFIRE data and the FSim model (Finney et al., 2011b) to inform managers as to the expected future volume of fire activity within a geographic area and the most cost effective allocation of resources within and between geographic areas. The FPA System allows managers to model the influence of various treatments on the burn probability of future large fires.

LANDFIRE provides wall-to-wall ecological information on current vegetation, successional dynamics, fire regime, terrain, fuels, and fire potential (Reeves et al., 2009; Rollins, 2009) (Table 1). Following, are examples to illustrate how LANDFIRE data has been used in Fuels Treatment, Restoration, and Wildfire Suppression.

4.1. LANDFIRE Use in fuels treatment and restoration

Although fire is generally recognized as a fundamental ecosystem process, there has been considerable debate as to the effectiveness of fuel treatments (Finney et al., 2005; Finney, 2007; Stephens et al., 2009; Prichard et al., 2010; Hudak et al., 2011; Graham et al., 2012; Safford et al., 2012). The comprehensive LANDFIRE dataset has allowed both management and research to evaluate fuel treatment effectiveness and restoration success at various project levels (Keane et al., 2007; Prichard et al., 2010; Reeves and Mitchell, 2011; Hollingsworth et al., 2012; Ottmar et al., 2012).

Several issues confound post-fire fuel treatment assessments (Martinson et al., 2003; Gibbons et al., 2012; Graham et al., 2012), making it difficult to assess their effectiveness and longevity. Understanding the environmental conditions and actual fire behavior when the fire entered the treatment area is crucial in determining treatment effectiveness. A treatment may have been intended to be successful under 90th percentile weather conditions but may have been unsuccessful at the 97th percentile level. In practice it can be difficult to determine actual conditions after the fact due to the uncertainty of local winds (Butler et al., 2006; Forthofer et al., 2011; Graham et al., 2012) and the convergence of multiple flame fronts (Finney and McAllister, 2011). Thus it is often impossible to determine if the treatment was under-designed, inadequately implemented, or inadequately maintained.

Even if a treatment is designed, implemented, and maintained well, it needs to be strategically placed to be effective at modifying fire spread across the landscape (Finney, 2001, 2006; Finney et al., 2005, 2007). LANDFIRE data and the models it supports provide a basis for gaming the landscape to improve the placement of landscape treatments. To date many fuels treatments which subsequently experienced fire did not have the full benefit of spatial data and decision support tools in their design (Finney et al., 2005; Cochrane et al., 2012). Several treatment design factors can be explored through fire modeling. The size of the treated area needs to be sufficiently large so as to significantly alter fire behavior in terms of spread rate, intensity, and spotting potential. The intensity of the treatment should vary depending on the goal of the treatment; for example, fuel-scape fragmentation vs. defensible space in proximity to resources that need to be protected (Moghaddas et al., 2010; Gibbons et al., 2012). Proper treatment modifies both the fireline intensity and severity (Graham et al., 2004), but may not reduce the size, particularly if light surface fuels support rapid fire spread within treated areas (Cochrane et al., 2012). Rapid spread does not, however, equate with severe outcomes (Ryan, 2002; Finney et al., 2005; Jackson et al., 2011; Safford et al., 2012).

Treatments need to be designed to be effective under the conditions in which they are likely to be tested by subsequent wildfire (Moghaddas et al., 2010). Climatology and future climate projections need to be taken into consideration with respect to fire weather drivers: wind direction and speed (Butler et al., 2004a,b; Werth, 2011), relative humidity, and fuel moisture. For example, the projected long axis of fire spread in Fig. 2a illustrates the influence of the dominant southwest fire season wind. In contrast the projected axis in Fig. 2b reflects the influence of the most severe northwest wind events. The size and intensity of fuels treatment need to vary to reflect these differences such that the intensity of the thinning prescription and size of thinned area around a protected resource should be different in the southwest vs. northwest quadrants with the goal of reducing fire-line intensity (Cohen, 2000), crowning (Alexander and Gruz, 2011; Cruz and Alexander, 2012), and spotting (Potter, 2011).

Altered fuel beds can affect fire behavior both within and adjacent to treated areas. Treatments can affect the severity or ecological consequences of fire within the treated area (Graham and Technical, 2003; Finney et al., 2005; Wimberly et al., 2009;

Cochrane et al., 2012) by modifying the intensity and duration of burning (Ryan, 2002). The manner in which a treated area burns can also affect spread, intensity, and spotting in adjacent areas and treatment "shadows" on the lee side of the treated area (Finney et al., 2005; Cochrane et al., 2012). Finney et al. (2005) analyzed the effect of prior fuels treatments on the spread and severity of the 2002 Rodeo-Chediski fire, which was then by far the largest fire in Arizona history. They found fires flanking through treated areas with reduced fire intensity and resultant severity in contrast to more intense head fires in heavier untreated fuels. Cochrane et al. (2012) used LANDFIRE and FARSITE to analyze the effect of fuels treatments on the Rodeo-Chediski, and 13 other major fires. They found fuels treatment enhanced fire spread in some portions of treatments but in other areas reduced fire spread depending on the local fuels and landscape position. Results illustrate that the treatments reduced fire severity but the fires still spread through the treated areas. This was emphasized during Arizona's 2011 218,000 hectare, 109 million dollar Wallow Fire, now the State's largest fire on record. Here, a series of recent prescribed burns on the White Mountain Fort Apache Indian Reservation was associated with reduced fuel loadings and stand densities. The reduced fire behavior and increased ease of fire line construction allowed tribal fire crews to burn out 43 km of fire line in two operational periods successfully limiting fire spread onto the Reservation on the Wallow's northwest flank (Jackson et al., 2011). Prior treatments are also credited with saving homes on the Wallow Fire (Bostwick et al., 2011).

It is often economically or logistically impractical, or ecologically unacceptable to treat a large enough area to form a protective barrier to fire spread or to preclude adverse site or landscape effects. This appears to be particularly true given the recent extremes in fire weather where historically unparalleled extremes of temperature, fire behavior indices, and drought are being reported on several continents (United Nations News, 2011). Climate change projections suggest continued severe and worsening fire weather (Moritz et al., 2012) which exacerbates the problem and reinforces the need to use models and data to strategically design and implement fuels treatments with an eye towards future threats. Case studies of treatment effectiveness on large Western fires indicate thinning to reduce canopy density followed by treatment of surface fuels is the most effective treatment (Agee and Skinner, 2005; Johnson et al., 2007; Wimberly et al., 2009; Bostwick et al., 2011; Hudak et al., 2011). Once successful treatments are implemented periodic retreatment is critical for maintaining effectiveness (Battaglia et al., 2008; Stephens et al., 2012). LANDFIRE data and vegetation dynamics models (Table 1) and fire behavior and effects models (Table 2) can help inform decisions on treatment location (e.g., FARSITE, FlamMap, Minimum Travel Time), intensity and timing of treatment (e.g., BehavePlus), and frequency of retreatment (e.g., LANDFIRE VDMs). A host of tools are available for LANDFIRE data-users to access and apply the data through the National Interagency, Fuels, Fire, and Vegetation Technology Transfer – FRAMES system (http://www.frames.gov/partner-sites/niftt/tools-and-user-documents/, accessed June 2012).

4.2. Wildfire Management

Although the primary driver for the creation of LANDFIRE was the need to make more strategic and effective investments in treating fuels and restoring landscapes, the same fuels and fire behavior science serves the fire management community (e.g., Fig. 2). The Wildland Fire Decision Support System (WFDSS) is a decision analysis and documentation system that assists fire managers and analysts in assessing risk for all types of wildland fires http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml, visited June 26, 2012). WFDSS is used by all federal agencies and some states to provide all levels of management with an overview of potential risk associated with an incident. This is accomplished through a web-based display of a fire perimeter, values at risk, land management objectives, weather, fire danger, and predicted fire behavior. The short-term, mid-term, or long-term fire behavior projections utilize LANDFIRE data in geospatial fire models. For example, FSPro (Finney et al., 2011a,b) output shows the probability of fire reaching parts of the landscape, which can be overlaid with values at risk information (Calkin et al., 2010, 2011; Thompson et al., 2011a,b) to evaluate trade-offs between suppression actions and the likelihood of impacts.

Table 4
Number of fire incidents, overall completed analyses, and published decisions, utilizing LANDFIRE data in the Wildland Fire Decision Support System (WFDSS) – LANDFIRE data use 2007 through late 2011. These numbers demonstrate a growing trend in the use of WFDSS, the use of analysis tools, and in the utilization of geospatial analysis tools to inform fire decision-making.

Year	Unique fire incidents	Total analyses completed with LANDFIRE data	Decisions published using geospatial fire analysis with LANDFIRE data
2007	216	619	0
2008	381	988	0
2009	7427	858	184
2010	12,872	837	187
2011	13,989	1808	236
Total	34,885	5110	607

The WFDSS interface has streamlined what was once an arduous task for analysts—locating, assembling, and piecing together data necessary to run the geospatial models, a task often complicated by data that were clipped to agency boundaries, or non-federal lands where data did not exist. In order to keep WFDSS tools relevant, LANDFIRE data layers are updated in response to large fires and fuels treatments in order to portray the landscape accurately for the next fire analysis. WFDSS includes several other tools related to smoke dispersion and costs (Noonan-Wright et al., 2011).

Fire managers use the tools provided in WFDSS to assess the situation, complete a risk analysis, document a strategic decision, and periodically reassess the situation as conditions change (Noonan-Wright et al., 2011). The number of fires where spatial analysis was used to inform management strategy has increased steadily as managers become more knowledgeable of the tools and gain confidence in their application (Table 4). Within the WFDSS database there have been numerous documented cases where managers chose not to utilize aggressive suppression actions to fully or immediately contain a fire when analysis indicated a low probability of fire reaching a critical area, or when the fire posed little threat to resource values. For example, several large fires burned in the Northern Rockies for most of the 2012 fire season, threatening infrastructure. The Mustang Fire, Halstead Fire and Trinity Ridge Fire each exceeded 58,000 ha (58,679 ha). Due to a prolonged fire season with multiple fires, firefighting resource shortages, and dangerous conditions such as increased potential for extreme fire behavior, steep and inaccessible terrain, and beetle-killed or fire-weakened snags, fire managers were not tasked with containing the fires; just to protect values that lay in their paths. This is a "point protection" strategy, meaning fires burned without suppression actions while fire crews put protection measures in place for isolated structures, moderated fire behavior specific areas so as not to damage sensitive resources, and otherwise protect isolated values at risk. GIS data coupled with landscape-scale fire behavior analyses (FlamMap, Near-Term, FSPro) were critical to identification of values, estimation of when the fire might reach them, and the estimated fire intensity upon impact in order to devise appropriate protection measures.

Analyses can guide managers in when it is safe to use fire to restore fire regimes and ecological processes, and when it is not. Ultimately, the safe reintroduction of fire in conjunction with sound wildfire management can substantially increase the area treated and the resilience of fire prone landscapes.

5. LANDFIRE future

The Federal Land Assistance, Management, and Enhancement (FLAME) of 2009 directed WFLC to develop the National Cohesive Wildland Fire Management Strategy (Cohesive Strategy) (http://www.forestsandrangelands.gov/strategy/index.shtml, accessed June 26, 2012). The goals of the Cohesive Strategy are to restore and maintain resilient landscapes, create fire-adapted communities, and to improve the safety and effectiveness of fire suppression. The strategy proposes to foster and use sound science to meet its goals. The three goals are interdependent and mutually reinforcing. By providing consistent, complete, up to date spatial data of vegetation, fuels, and fire potential LANDFIRE data support all three goals. LANDFIRE data and the models it supports are the primary state of knowledge tools available to the fire management community. The data and models have been institutionalized in that managers are required to use the tools in planning, justifying, and documenting actions.

LANDFIRE is the result of integration of remote sensing, vegetation inventory, and ecosystem process modeling (Rollins, 2009). Each of these fields is robust and dynamic, as is the land the data represent. Like all remote sensing-, modeling-, and monitoring-based data products LANDFIRE data have a finite ‘‘shelf-life.’’ The processes for data updating reflecting management activities or fires under NFPORS or MTBS (Vogelmann et al., 2011), respectively, cannot capture incipient landscape changes due to succession or subtle shifts due to insect and disease activity or land uses such as grazing. Given its integral role as the primary data source for modeling potential fire behavior and effects in fuels treatment, restoration, or suppression planning there needs to be a sustained effort to update and improve the data. The effort needs to direct research to improve critical relationships and integrate emerging science into improved data for modeling potential fire behavior and effects in support of the high priority national need to reduce the costs and losses from wildfires.

6. Conclusions

The creation of LANDFIRE is an integral part of a much larger effort to improve the safety and cost-effectiveness of fire management activities. It is part of the Cohesive Strategy that has been evolving for 12 years. The current Cohesive Strategy is just that, a strategy. It is not a strict prescriptive formula for success in dealing with the increasingly complex and severe wildland fire problem. It is a journey driven by increasing social need and needs to be built on new information, better science, better models, and better data.

Landfire and a suite of decision support tools provide the means to game the landscape to design cost effective treatment alternatives. Data provide inputs to suite of fire behavior and effects models used to support local, regional, and national strategic planning and policy decisions. They provide input to inform local to regional strategic and tactical decisions on proposed management and suppression activities. Data need to be updated to reflect vegetation/fuel changes and to incorporate emerging science. The large fire problem is not going to go away but, with increased public awareness and commitment, managers and policy makers supported by robust science can reduce the mega-negative consequences of future fires.

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References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211, 83–96.

Alexander, M.E., Gruz, M., 2011. Crown fire dynamics in conifer forests. In: Werth, P.A., Potter, B.E., Clements, C.B., Finney, F.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A., McAllister, S.S. (Eds.), Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, OR. General Technical Report, PNW-GTR-854.107-144 (Chapter 8).

Anderson, H.E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. General Technical Report INT-122. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 22p.

Andrews, P.L., 2009. BehavePlus Fire Modeling System, version 5.0: Variables. RMRS-GTR-213, 124p. <http://www.fs.fed.us/rm/pubs/rmrs_gtr213.pdf> (accessed 06.12).

Barrett, S.W., Havlina, D., Hann, W.J., 2011. Fire regime condition class: concepts, methods, and applications. In: Wade, D.D., Robinson, M.L. (Eds.), Proceedings of 3rd Fire Behavior and Fuels Conference, October 25–29, 2010, Spokane, Washington, USA. International Association of Wildland Fire, Birmingham, Alabama, USA, CD, 17p.

Battaglia, M.A., Smith, F.W., Shepperd, W.D., 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? Forest Ecology and Management 256, 2029–2038.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449. http://dx.doi.org/10.1126/science.1155121.

Bostwick, P., Menakis, J., Sexton, T., 2011. How Fuel Treatments Saved Homes from the Wallow Fire, 14p. http://www.fs.fed.us/fire/management/fuel_treatments.pdf.

Bushey, C.L., 1989. The 1988 Fire Season in the Northern Rocky Mountains: A Chronology of Weather, Fire Occurrence, Behavior and Growth. U.S. Department of Agriculture, Forest Service, Missoula, MT, 369p (Report on file at Missoula Fire Sciences Laboratory).

Butler, B.W., Bartlette, R.A., Bradshaw, L.S., Cohen, J.D., Andrews, P.L., Putnam, T., Mangan, R.J., 1998. Fire Behavior Associated with the 1994 South Canyon Fire on Storm King Mountain. Colorado. Res. Pap. RMRS-RP-9. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, 82p.

Butler, B.W., Finney, M.A., Andrews, P., Albini, F.A., 2004a. A radiation-driven model for crown fire spread. Canadian Journal Forest Research 34, 1588–1599.

Butler, B.W., Cohen, J.D., Latham, D.J., Schuette, R.D., Sopko, P., Shannon, K.S., Jimenez, D., Bradshaw, L.S., 2004b. Measurements of radiant emissive power and temperatures in crown fires. Canadian Journal of Forest Research 34, 1577–1587.

Butler, B., Finney, M., Bradshaw, L., Forthofer, J., McHugh, C., Stratton, R., Jimenez, D., 2006. WindWizard: a new tool for fire management decision support. In: Andrews, Patricia L., Butler, Bret W., comps. (Eds.), Fuels Management—How to Measure Success: Conference Proceedings, 28–30 March 2006. Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Pgs. 787–796.

Calkin, D.E., Ager, A.A., Gilbertson-Day, J. (Eds.), 2010. Wildfire Risk and Hazard: Procedures for the First Approximation. General Technical Report RMRS-GTR-235. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 62p.

Calkin, D.E., Ager, A.A., Thompson, M.P. (Eds.), 2011. A Comparative Risk Assessment Framework for Wildland Fire Management: The 2010 Cohesive Strategy Science Report. General Technical Report RMRS-GTR-262. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 63p.

Cochrane, M.A., Moran, C.J., Wimberly, M.C., Baer, A.D., Finney, M.A., Beckendorf, K.L., Eidenshink, J., Zhu, Z., 2012. Estimation of wildfire size and risk changes due to fuels treatments. International Journal of Wildland Fire 21 (4), 357–367.

Cohen, J.D., 2000. Preventing disaster: home ignitability in the wildland-urban interface. Journal of Forestry 98, 15–21.

Cruz, M.G., Alexander, M.E., 2012. Evaluating regression model estimates of canopy fuel stratum characteristics in four crown fire-prone fuel types in western North America. International Journal of Wildland Fire 21, 168–179.

Eidenshink, J., 2012. LANDFIRE User Access and Download Statistics. USGS EROS Center, Sioux Falls, SD (personal communication, graphs on file at Missoula Fire Sciences Laboratory).

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z., Quayle, B., Howard, S., 2007. A project for monitoring trends in burn severity. Fire Ecology 3, 3–21. http://dx.doi.org/10.4996/FIREECOLOGY.0301003.

Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science 47, 219–228.

Finney, M.A., 2002. Fire growth using minimum travel time methods. Canadian Journal of Forest Research 32 (8), 1420–1424.

Finney, M.A., 2004. FARSITE: Fire Area Simulator – Model Development and Evaluation. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-4 Revised. Fort Collins, CO, 47p.

Finney, M.A., 2006. An overview of flammap fire modeling capabilities. In: Andrews, P.L., Butler, B.W., comps. (Eds.), Fuels Management—How to Measure Success: Conference Proceedings, 2006 28–30 March, Portland, OR. Proceedings RMRS-P-41. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 213–219.

Finney, M.A., 2007. A computational method for optimizing fuel treatment locations. International Journal of Wildland Fire 16, 702–711.

Finney, M.A., McAllister, S.S., 2011. Fire interactions and mass fires. In: Werth, P.A., Potter, B.E., Clements, C.B., Finney, F.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A., McAllister, S.S. (Eds.), Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report, PNW-GTR-854, Portland, OR, pp. 49–71 (Chapter 4).

Finney, M.A., Ryan, K.C., 1995. Use of the FARSITE fire growth model for fire prediction in U.S. National Parks. In: The International Emergency Management and Engineering Conference, 1995 May 9–12, Nice, France, pp. 183–189.

Finney, M.A., McHugh, C.W., Grenfell, I.C., 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35, 1714–1722. http://dx.doi.org/10.1139/X05-090.

Finney, M.A., Grenfell, I.C., McHugh, C.W., Seli, R.C., Trethewey, D., Stratton, R.D., Brittain, S., 2011a. A method for ensemble wildland fire simulation. Environmental Modeling and Assessment 16, 123–167.

Finney, M.A., McHugh, C.E., Grenfell, I.C., Riley, K.L., Short, K.C., 2011b. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment 25, 973–1000.

Forthofer, J.M., Shannon, K.S., Butler, B.W., 2011. Initialization of high resolution surface wind simulations using National Weather Service (NWS) gridded data. In: Proceedings of 11th International Wildland Fire Safety Summit, Missoula, MT, April 4–8, 2011. International Association of Wildland Fire, CD.

Gibbons, P., van Bommel, L., Gill, A.M., Cary, G.J., Driscoll, D.A., Bradstock, R.A., Knight, E., Moritz, M.A., Stephens, S.L., Lindenmayer, D.B., 2012. Land management practices associated with house loss in wildfires. PLoS ONE 2012 (7), e29212.

Graham, R.T. (Technical Editor), 2003. Hayman Fire Case Study. General Technical Report RMRSGTR-114. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, 396p.

Graham, R.T., McCaffrey, S., Jain, T.B., 2004. Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-120 (Ogden, UT).

Graham, R., Finney, M., McHugh, C., Cohen, J., Stratton, R., Bradshaw, L., Nikolov, N., Calkin, D., 2012. Fourmile Canyon Fire Findings. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-289. Ft. Collins, CO, 110 p.

Guth, A.R., Cohen, S.B., 1991. Red Skies Of '88 The 1988 Forest Fire Season In The Northern Rockies, The Northern Great Plains and The Greater Yellowstone Area. Publisher: Pictorial Histories Pub Co., 124p. ISBN: 0-929521-17-X Paperback.

Hollingsworth, L.T., Kurth, L.L., Parresol, B.R., Ottmar, R.D., Prichard, S.J., 2012. A comparison of geospatially modeled fire behavior and fire management utility of three data sources in the southeastern United States. Forest Ecology and Management 273, 43–49.

Hood, S.M., Miller, M. (Eds.), 2007. Fire Ecology and Management of the Major Ecosystems of Southern Utah. USDA, Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-202. Fort Collins, CO, 110p.

Hudak, A.T., Rickert, I., Morgan, P., Strand, E., Lewis, S.A., Robichaud, P.R., Hoffman, C., Holden, Z.A., 2011. Review of Fuel Treatment Effectiveness in Forest and Rangelands and a Case Study from the 2007 Megafires in Central Idaho, USA. USDA Forest Service, Rocky Mountain. Research Station, General Technical Report RMRS-GTR-252 (Fort Collins, CO).

Jackson, M., Taber, M., Nosie, C. Jr., Whiteaker, R., Kelly, K., Keller, P., 2011. Wallow Fire Fuel Treatment Effectiveness on the Fort Apache Indian Reservation. Report on Wildfire Lessons Learned Center. 20p. <http://wildfirelessons.net/documents/Wallow_FTA_FTE.pdf> (accessed 06.12).

Johnson, M.C., Peterson, D.L., Raymond, C.L., 2007. Guide to Fuel Treatments in Dry Forests of the Western United States: Assessing Forest Structure and Fire Hazard. General Technical Report PNW-GTR-686. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, 322p.

Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), 2009. Global Climate Change Impacts in the United States, Cambridge University Press, 32 Avenue of the Americas, New York, NY, 189p. ISBN: 978-0-521-14407-0 paperback.

Keane, R.E., Hardy, C.C., Ryan, K.C., Finney, M.A., 1997. Simulating effects of fire on gaseous and atmospheric carbon fluxes from coniferous forest landscapes. World Resource Review 9 (2), 177–203.

Keane, R.E., Long, D.G., Basford, D., Levesque, B.A., 1997b. Simulating vegetation dynamics across multiple scales to assess alternative management strategies. In: Conference Proceedings – GIS 97, 11th Annual Symposium on Geographic Information Systems – Integrating Spatial Information Technologies for tomorrow, February 17–20, 1997, Vancouver, British Columbia, Canada. GIS World, INC, pp. 310–315.

Keane, R.E., Long, D.G., Schmidt, K.M., Mincemoyer, S., Garner, J.L. 1998a. Mapping fuels for spatial fire simulations using remote sensing and biophysical modeling. In: J.D. Greer (Ed.), Proceedings of the Seventh Forest Service Remote Sensing Applications Conference. Nassau Bay, Texas, April 6–April 10, 1998. American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 301–316.

Keane, R.E., Garner, J.L., Schmidt, K.M., Long, D.G., Menakis, J.P., Finney, M.A., 1998b. Development of Input Spatial Data Layers for the FARSITE Fire Growth Model for the Selway–Bitterroot Wilderness Complex, USA. USDA Forest Service General Technical Report RMRS-GTR-3, 66p.

Keane, R.E., Mincemoyer, S.A., Schmidt, K.M., Menakis, J.P., Long, D.G., Garner, J.L., 2000a. Mapping Vegetation and Fuels for Fire Management on the Gila National Forest Complex. USDA Forest Service General Technical Report RMRS-GTR-46-CD.

Keane, R.E., Mincemoyer, S.A., Kirsten M., Schmidt, K.M., Garner, J.L., 2000b. Mapping fuels for fire management on the Gila National Forest Complex, New Mexico. In: Neuenschwander, L.N., Ryan, K.C., Golberg, G., Greer, J.0 (Eds.), Proceedings from the Joint Fire Sciences Conference and Workshop ''Crossing the Millennium: Integrating Spatial Technologies and Ecological Principles for a New Age in Fire Management'', Boise, ID. University of Idaho Press. Moscow, ID, pp. 193–205.

Keane, R.E., Burgan, R.E., Van Wagtendonk, J., 2001. Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. Journal of Wildland Fire 10 (3–4), 301–319.

Keane, R.E., Ryan, K.C., Veblen, T.T., Allen, C.D., Logan, J.A., Hawkes, B., 2002a. The cascading effects of fire exclusion in rocky mountain ecosystems. In: Baron, J.S. (Ed.), Rocky Mountain Futures, An Ecological Perspective. Island Press, Washington, pp. 133–152.

Keane, R.E., McNicoll, C., Rollins, M.G., Parsons, R.A., 2002b. Integrating Ecosystem Sampling, Gradient Modeling, Remote Sensing, and Ecosystem Simulation to Create Spatially Explicit Landscape Inventories. General Technical Report RMRS-GTR-92, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Keane, R.E., Rollins, M., Zhu, Z.L., 2007. Using simulated historical time series to prioritize fuel treatments on landscapes across the United States: the LANDFIRE prototype project. Ecological Modeling 204, 485–502.

Kostishack, P., Rana, N., 2002. An Introduction to the National Fire Plan History, Structure, and Relevance to Communities. Pinchot Institute for Conservation, Washington, DC, 56p.

Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecological Applications 19, 1003–1021.

Long, D.G., Ryan, K.C., Stratton, R.D., Mathews, E., Scott, J., Mislivits, M., Miller, M., Hood, S.M., 2003. Modeling the effects of fuel treatments for the Southern Utah Fuel Management Demonstration Project. In: Omi, P.N., Joyce, L.A. (Eds.), Proceedings of the Fire, Fuel Treatments, and Ecological Restoration Conference, April 16–18, 2002, Fort Collins, CO. RMRS-P29. U.S. Department of Agriculture, Forest Service, pp. 387–396.

Lutes, D.C., Keane, R.E., Caratti, J.F., 2009. A surface fuels classification for estimating fire effects. International Journal of Wildland Fire 18, 802–814.

Martinson, E., Omi, P.N., Shepperd, W., 2003. Effects of fuel treatments on fire severity, Part 3. In: Graham, R.T. (Technical Editor). Hayman Fire Case Study. General Technical Report RMRSGTR-114. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 96–126.

Menakis, J.P., Keane, R.E., Long, D.G., 2000. Mapping ecological attributes using an integrated vegetation classification system approach. Journal of Sustainable Forestry 11 (1/2), 245–265.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17, 2145–2151.

Moghaddas, J.J., Collins, B.M., Menning, K., Moghaddas, E.E.Y., Stephens, S.L., 2010. Treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada. Canadian Journal Forest Research 40 (9), 1751–1765.

Moritz, M.A., Parisien, M.-A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., Hayhoe, K., 2012. Climate change and disruptions to global fire activity. Ecosphere 3(6), 49, 22p. <http://dx.doi.org/10.1890/ES11-00345.1>.

Noonan-Wright, E.K., Opperman, T.S., Finney, M.A., Zimmerman, G.T., Seli, R., Elenz, L.M., Calkin, D.E., Fiedler, J.R., 2011. Developing the US Wildland Fire Decision Support System. Journal of Combustion, 2011, 14p (Article ID 168473).

North American Forestry Commission, 2012. Responding to Increasing and Changing Demands in Fire Management. <http://www.fao.org/docrep/meeting/024/md503e.pdf> (visited 06.26.12).

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J., 2007. An overview of the fuel characteristic classification system—quantifying, classifying, and creating fuelbeds for resource planning. Canadian Journal of Forest Research 37, 2383–2393.

Ottmar, R.D., Blake, J.I., Crolly, W.T., 2012. Using fine-scale fuel measurements to assess wildland fuels, potential fire behavior and hazard mitigation treatments in the southeastern USA. Forest Ecology and Management 273, 1–3.

Potter, B.E., 2011. Spot fires. In: Werth, P.A., Potter, B.E., Clements, C.B., Finney, F.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A., McAllister, S.S. (Eds.), Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical, Report, PNW-GTR-854, pp. 81–87 (Chapter 6).

Prichard, S.J., Ottmar, R.D., Anderson, G.K., 2007. Consume User's Guide and Scientific Documentation, 235p. <http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf> (accessed 06.12).

Prichard, S.J., Peterson, D.L., Jacobson, K., 2010. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Canadian Journal of Forest Research 40, 1615–1626.

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., McKeefry, J.F., 2005. The wildland-urban interface in the United States. Ecological Applications 15, 799–805.

Reeves, M.C., Mitchell, J.E., 2011. Extent of coterminous US rangelands: quantifying implications of differing agency perspectives. Rangeland Ecology and Management 64, 585–597.

Reeves, M.C., Ryan, K.C., Rollins, M.G., Thompson, T.G., 2009. Spatial fuel data products of the LANDFIRE Project. International Journal of Wildland Fire 18 (3), 250–267.

Reinhardt, E.D., 2007. Using FOFEM 5.0 to Estimate Tree Mortality, Fuel Consumption, Smoke Production, and Soil Heating from Wildland Fire, 7p. <http://www.firelab.org/science-applications/fire-fuel/111-fofem> (accessed 06.12).

Rollins, M.G., 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire 18 (3), 235–249.

Rollins, M.G., Frame, C.K. (Technical Editors), 2006. The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management. General Technical Report RMRS-GTR-175. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research. Station, Fort Collins, 416p.

Roose, C.I., Swetnam, T.W., 2012. 1416-year reconstruction of annual, multidecadal, and centennial variability in area burned for ponderosa pine forests of the southern Colorado Plateau region, Southwest USA. The Holocene 22 (3), 281–290.

Rothermel, R.C., Hartford, R.A., Chase, C.H., 1994. Fire Growth Maps for the 1988 Greater Yellowstone Area Fires. General Technical Report INT-304. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, 64p.

Ryan, K.C., 1991. Vegetation and wildland fire: implications of global climate change. Environment International 17, 169–178.

Ryan, K.C., 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36 (1), 13–39.

Safford, H.D., Stevens, J.T., Merriam, K., Meyer, M.D., Latimer, A.M., 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. Forest Ecology and Management 274, 17–28.

Schmidt, K.M., Menakis, J.P., Hardy, C.C., Hann, W.J., Bunnell, D.L., 2002. Development of Coarse-scale Spatial Data for Wildland Fire and Fuel Management. General Technical Report RMRS-GTR-87. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, 41p.

Scott, J.H., Burgan, R.E., 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-153, Fort Collins, CO, 72p.

Scott, J.H., Reinhardt, E.D., 2001. Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior. Res. Pap. RMRS-29. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 59p.

Stephens, S.L., Moghaddas, J.J., Edminster, C., Fiedler, C.E., Haase, S., Harrington, M., Harrington, M., Keeley, J.E., Knapp, E.E., McIver, J.D., Metlen, K., Skinner, C.N., Youngblood, A., 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications 19, 305–320.

Stephens, S.L., McIver, J.D., Boerner, R.E.J., Fettig, C.J., Fontaine, J.B., Hartsough, B.R., Kennedy, P.L., Schwilk, D.W., 2012. The effects of forest fuel-reduction treatments in the United States. BioScience 62, 549–560.

Stratton, R.D., 2004. Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. Journal of Forestry 102, 32–40.

Thompson, M.P., Calkin, D.E., Finney, M.A., Ager, A.A., Gilbertson-Day, J.W., 2011a. Integrated national-scale assessment of wildfire risk to human and ecological values. Stochastic Environmental Research and Risk Assessment. http://dx.doi.org/10.1007/s00477-011-0461-0.

Thompson, M.P., Calkin, D.E., Gilbertson-Day, J.W., Ager, A.A., 2011b. Advancing effects analysis for integrated, large-scale wildfire risk assessment. Environmental Monitoring and Assessment 179, 217–239.

United Nations News, 2011. Mega-fires may be Contributing to Climate Change. <http://www.un.org/apps/news/story.asp?NewsID=38325&Cr=climate±change&Cr1> (visited 06.26.12).

USDI, USDA, Department of Energy, Department of Defense, Department of Commerce, US Environmental Protection Agency, Federal Emergency Management Agency, National Association of State Foresters, 2001. 'Review and update of the 1995 Federal Wildland Fire Management Policy.' (Bureau of land Management, Office of Fire and Aviation: Boise, ID). <http://www.nifc.gov/policies/policies_documents/GIFWFMP.pdf> (accessed 06.120.

Vogelmann, J.E., Kost, J.R., Tolk, B., Howard, S., Short, K., Chen, X., Chengquan Huang, C., Pabst, K., Rollins, M.G., 2011. Monitoring landscape change for LANDFIRE using multi-temporal satellite imagery and ancillary data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 4 (2), 252–264.

Werth, P.A., 2011. Critical fire weather patterns. In: Werth, P.A., Potter, B.E., Clements, C.B., Finney, F.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A., McAllister, S.S. (Eds.), Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. General Technical, Report, PNW-GTR-854, Portland, OR. pp. 25–48.

White, J.D., Running, S.W., Nemani, R., Keane, R.E., Ryan, K.C., 1997. Measurement and remote sensing of LAI in Rocky Mountain montane ecosystems. Canadian Journal of Forest Research 27, 1714–1727.

Williams, J., Hamilton, L., 2005. The Mega-fire Phenomenon: Toward a More Effective Management Model – A Concept Paper. The Brookings Institution. Center for Public Policy Education, Washington, DC, 19p.

Williams, J., Albright, D., Hoffmann, A.A., Eritsov, A., Moore, P., Mendes de Morais, J.C., Leonard, M., San Miguel-Ayanz, J., Xanthopoulos, G., Van Lierop, P., 2011. Findings and implications from a coarse-scale global assessment of recent selected mega-fires. In: 5th International Wildland Fire Conference, Sun City, South Africa, 9–13 May 2011, 19p.

Wimberly, M.C., Cochrane, M.A., Baer, A.D., Pabst, K., 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications 19, 1377–1384.

Zimmerman, T., Kurth, L., Burgard, M., 2011. The Howling Prescribed Natural Fire – long-term effects on the modernization of planning and implementation of wildland fire management. In: Proceedings of 3rd Fire Behavior and Fuels Conference, October 25–29, 2010, Spokane, Washington, USA Published Electronically by the International Association of Wildland Fire, Birmingham, Alabama, USA, 9p.