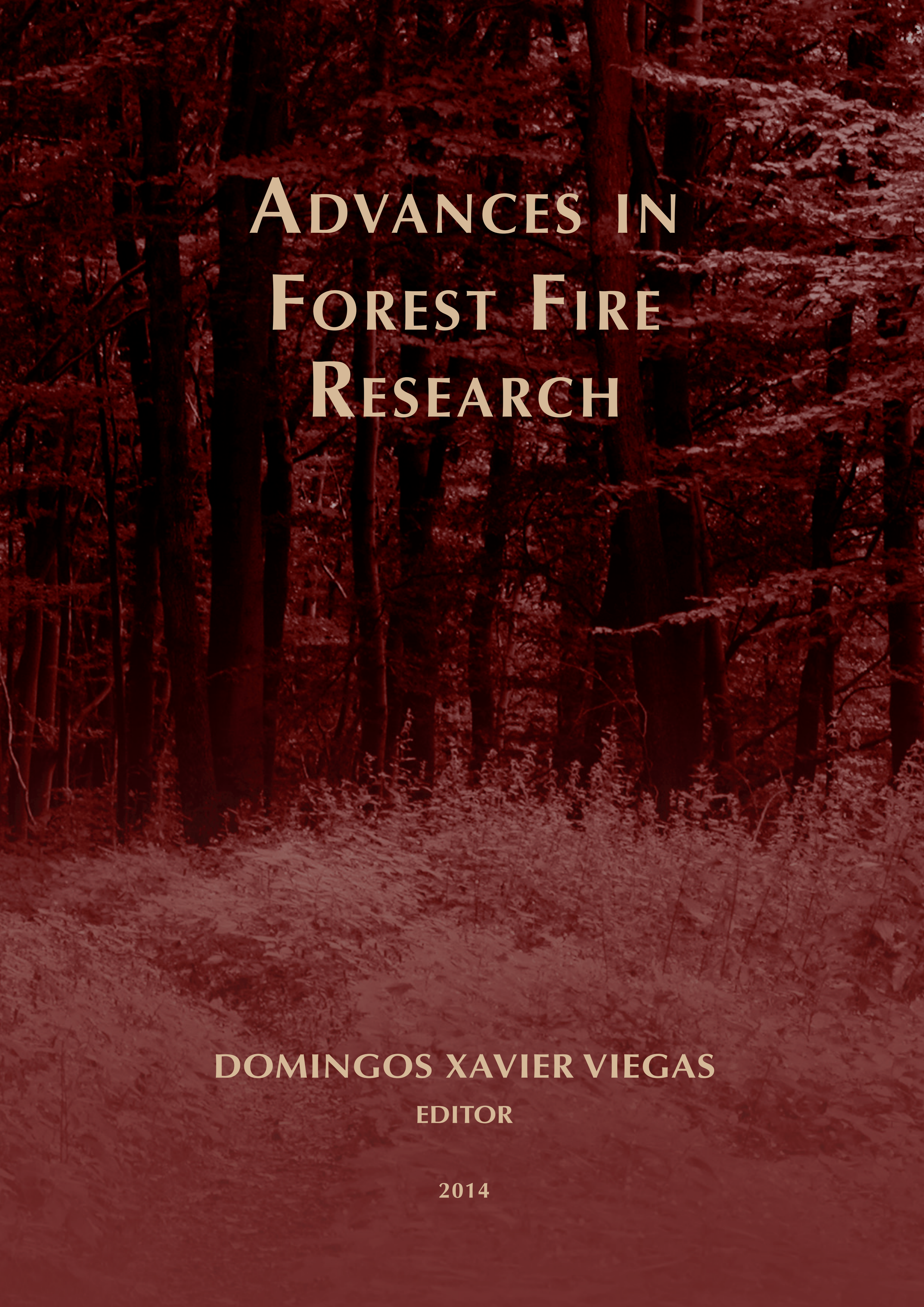

ADVANCES IN FOREST FIRE RESEARCH

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Application of simulation modeling for wildfire risk assessment and management

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Abstract

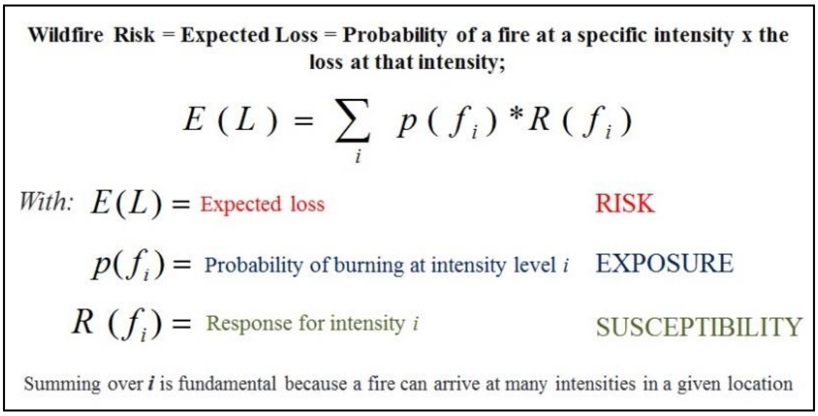
The growing incidence of large wildfires impacting urban interfaces and values of interest over the past decades has led to extensive research on decision support tools for fire risk assessment and management. The inherent complexity of risk management and fuel treatment planning has led to a rapid increase in the application of fire spread and behavior modeling software for both research and operational applications. Simulation models are now routinely used to analyze potential fire behavior and to develop risk assessments and mitigation strategies, over a range of scales, from forest stands (a few hectares) to large landscapes. Fire behavior models mainly used for fuels planning in the US and elsewhere include NEXUS, FVS-FFE, FARSITE, FlamMap, RANDIG, and FSIM. The geospatial interface to these models, ArcFuels, is used to streamline preparation of input files and post-process simulation outputs. The majority of these landscape fire simulation models use the minimum travel time algorithm, a compact fire simulation algorithm that makes it computationally feasible to simulate thousands of fires and generate burn probability and intensity maps over large areas. The outputs can be used to study wildfire topology on complex landscapes, and analyze uncertainty associated with wildfire events in terms of timing, location, intensity, and duration. Wildfire simulation models have also been coupled with spatial optimization software to design efficient landscape fuel treatment plans. From a risk assessment standpoint, the key benefit of newer wildfire simulation approaches, compared to previous work on spatial patterns in ignition patterns, is that the former accounts for risk factors that influence landscape wildfire spread, while the latter does not. Overall, properly calibrated and validated, wildfire simulation methods offer a dramatic increase in information content for conservation, restoration, and fire protection planning on fire-prone landscapes. Risk assessments using simulation methods have now been completed for a range of issues including carbon offsets, endangered wildlife species, habitat conservation, watersheds and WUI protection, and protection of biodiversity. In this talk, we will discuss the application of wildfire simulation models and geospatial tools for wildfire risk assessment and management for several study areas including the western US and the Mediterranean Basin.

1. Introduction

To reduce the growing financial and ecological losses from large wildfires, risk assessment and cost-effective mitigation activities have become a challenge for planners, policy makers, fuel managers and

Forest Services (Ager *et al.* 2011; Calkin *et al.* 2011). The relevant importance of wildfire risk assessment and fuel management will play a key role with urban expansion into the wildlands, land use variations and climate-change effects on fire occurrence frequency, burn probability, fire intensity and the related consequences (Brown *et al.* 2004; Westerling *et al.* 2006; Moreira *et al.* 2011; Arca *et al.* 2012; Kloster *et al.* 2012; Brotons *et al.* 2013; Ager *et al.* 2014). Since weather and topography are beyond human control (Finney 2007), wildfire mitigation activities encompass a wide range of operational methods including thinning, mechanical treatments for limiting fuel load and continuity, prescribed burning, and creation of infrastructures and fuelbreaks (Agee and Skinner 2005; Montiel and Kraus 2010). These activities have the aim of reducing both surface and canopy fuel load and continuity, to ultimately bring down the occurrence of uncharacteristic wildfires (Agee *et al.* 2000; Cochrane *et al.* 2012). Fire mitigation projects vary widely depending on ecosystems and ecological conditions, a strong role being played by historical fire regimes, weather, topography, and the spatial pattern of values at risk. For instance, some treatments are designed as localized fuelbreaks to minimize fire occurrence within highly valued social and ecological values as well as susceptibility, while others are designed to impede or slow down the spread of fire over large landscapes (Ager *et al.* 2011).

In this paper, we define fire risk as the expected loss or benefit after the fire, and fire exposure as the analysis of the probability of a fire at given intensities (Figure 1; Fairbrother and Turnley 2005; Finney 2005; Salis *et al.* 2013). We define risk factors as the individual contributing components to risk (likelihood, intensity and susceptibility). Quantitative assessment of wildfire risk requires (a) the probability of a fire at a specific location; (b) the conditional fire intensity, measured by flame length; (c) the resulting net value change in financial or ecological value (Finney 2005; Miller and Ager 2013). Wildfire exposure is a necessary step in risk assessment and does not include the quantification of expected wildfire impacts.



Wildfire Risk = Expected Loss = Probability of a fire at a specific intensity x the loss at that intensity;

$$E(L) = \sum_i p(f_i) * R(f_i)$$

With: $E(L) =$ Expected loss — RISK

$p(f_i) =$ Probability of burning at intensity level i — EXPOSURE

$R(f_i) =$ Response for intensity i — SUSCEPTIBILITY

Summing over ***i*** is fundamental because a fire can arrive at many intensities in a given location

Figure 1. Overview of the definition used for fire risk, exposure, and susceptibility in this paper

From a risk standpoint, it is important to note that in all ecosystems a very small proportion of wildfires globally accounts for most of the burned area, as well as the resulting damages and human casualties: thus, accounting for the risk posed by large destructive wildfires requires consideration of their behavior and spread over large areas (Viegas 2004; Finney *et al.* 2005; Viegas *et al.* 2006; Ager *et al.* 2010*a*, 2013; Salis *et al.* 2013). The complexity of fire risk assessment and management and the abovementioned points have led to a rapid increase in the application of fire behavior modeling software in both research and operational contexts. Simulation models are now routinely used to analyze potential fire behavior and to develop risk assessments and mitigation strategies, over a range of scales, from forest stands (a few hectares) to landscapes (< 10^5 ha), regional (< 10^7 ha) or national scales (Calkin *et al.* 2011). Fire behavior models used for fuels planning include NEXUS (Scott 1999), BehavePlus (Andrews 2007), FVS-FFE (Rebain 2010), FARSITE (Finney 1998), FlamMap (Finney 2006), RANDIG (Finney 2002), and FSIM (Finney *et al.* 2011). The geospatial interface to these models, ArcFuels, is used to streamline preparation of input files and post-process simulation outputs (Vaillant *et al.* 2013). To analyze uncertainty associated with wildfire events in terms of timing, location, rate of spread, intensity, and duration, simulation of thousands fires at landscape scales are commonly performed. A number of supporting models and software can be used, in conjunction with historical databases, to estimate appropriate wind, weather, dead and live fuel moisture, and other input variables required to run a fire behavior model (Nelson 2000; Butler *et al.* 2006; Stratton 2006; Forthofer 2007). While the application of non-spatial fire behavior models for a single fuel type and constant weather conditions is relatively straightforward, the design and evaluation of large-scale risk assessment and management activities requires more complex landscape fire modeling to fully characterize fire exposure and potential effects of events burning with diverse conditions in an area. The abovementioned issues have created a strong demand for an integrated modeling system to assess current wildfire exposure and risk, and to analyze the potential benefits of proposed fuel management and other mitigation activities (Miller and Ager 2013). The majority of these landscape fire simulation models use the minimum travel time algorithm (MTT, Finney 2002), a compact fire simulation algorithm that makes it computationally feasible to simulate thousands of fires and generate burn probability and intensity maps over large areas (Ager *et al.* 2012). The MTT algorithm searches for the fastest path of fire spread along straight-line transects connected by the cell corners (nodes) (Figure 2; Finney 2002, 2006): MTT pathways are then interpolated to reveal the fire perimeter positions at specific instants in time.

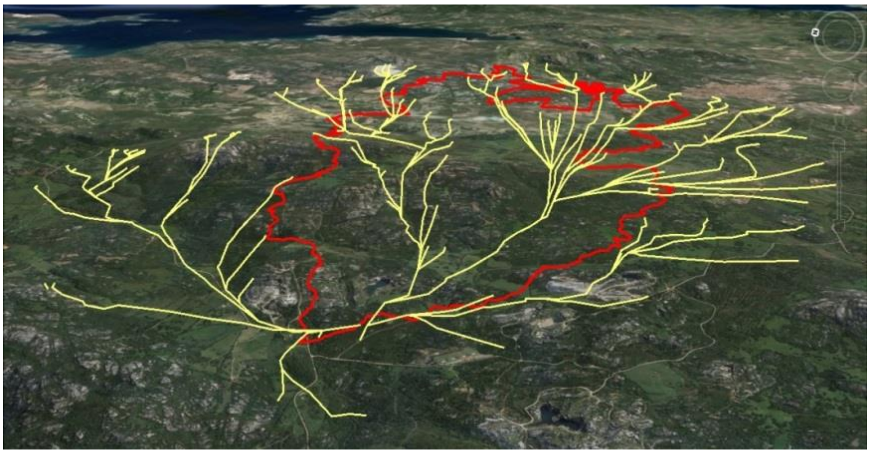


Figure 2. Major fire flow paths (yellow) and observed wildfire perimeter (red) over an aerial photograph. The flow paths, obtained by the MTT spread algorithm, searches for the fastest path of fire spread along straight-line transects connected by nodes. The example refers to a wildfire occurred in North-East Sardinia, Italy (Lu Lioni, Arzachena, August 2004).

The outputs can be used to study wildfire topology on complex landscapes, and analyze uncertainty associated with wildfire events in terms of timing, location, intensity, and duration. Wildfire simulation models have also been coupled with spatial optimization software to design efficient landscape fuel treatment plans (Finney 2006; Seli *et al.* 2008). From a risk assessment standpoint, the key benefit of newer wildfire simulation approaches, compared to previous works on spatial patterns in ignition occurrence patterns, is that the former accounts for risk factors that influence landscape wildfire spread, while the latter does not (Ager *et al.* 2011, 2014). Overall, properly calibrated and validated, wildfire simulation methods offer a dramatic increase in information content for conservation, restoration, and fire protection planning on fire-prone landscapes (Arca *et al.* 2007; Ager *et al.* 2007, 2010*a*; Salis *et al.* 2013). Risk assessments using simulation methods have now been completed for a range of issues including carbon offsets, wildlife habitat conservation, WUI protection, and protection of biodiversity. In this paper, we will discuss the application of wildfire simulation models and geospatial tools for wildfire risk assessment and management for several study areas including the western US and the Mediterranean Basin.

2. **Methods**

The majority of fire behavior models are derived from systems that model one-dimensional fire behavior as part of a spreading line fire. Most models linked or integrated Rothermel’s models for predicting surface and crown fire rates of spread with VanWagner’s or Scott’s crown fire transition and propagation models, and provided outputs of diverse fire behavior characteristics (rate of spread, fireline intensity, flame length, crown fire activity, etc.) (Rothermel 1972; Anderson 1983, Van Wagner 1993; Scott and Reinhardt 2001). In depth discussions of these models and their limitations, as well as programs and tools to determine appropriate weather inputs, to select fuel management scenarios, or to streamline preparation of input files and post-process simulation outputs, can be found in several recent papers, as presented in the Introduction.

The minimum travel time (MTT) fire spread algorithm of Finney (2002) is one of the most used to analyze fire exposure and characterize fire behavior. The MTT algorithm has been extensively described elsewhere and is routinely applied to fire management problems in the US and elsewhere; initial calibration (Figure 2) and validation of the Rothermel’s fire spread model as implemented in FARSITE and the MTT were performed and described by several research papers (Ager *et al.* 2007, 2012; Arca *et al.* 2007; Duguy *et al.* 2007; Andrews 2009; Salis 2008; Salis *et al.* 2013, 2014).

FlamMap MTT utilizes the same set of gridded spatial inputs as the FARSITE simulation system. The spatial inputs include eight grid themes that describe fuel canopy characteristics, surface fuel model, and topography, which are combined into a binary landscape (LCP) file (Figure 3; Finney 1998). Surface fuels are described by fuel models that characterize dead and live fuel load (by size class), surface-area-to-volume ratio for live and dead fuels, fuelbed depth, moisture of extinction, and heat content. Fuel models are derived by field measurements, selected using photo guides, or obtained from other data sources (Anderson 1982; Scott and Burgan 2005; Arca *et al.* 2009). Canopy fuels are described by percentage of cover, crown bulk density, crown base height, and average height.

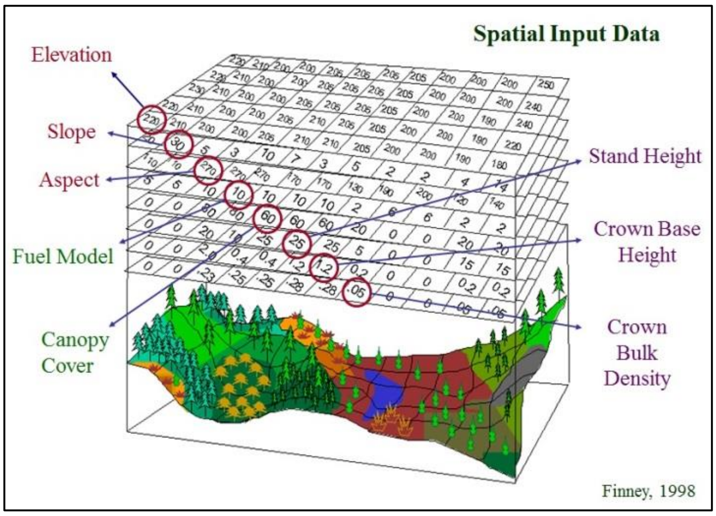


Figure 3. Topography, surface and crown fuels grid data used for wildfire simulations by FlamMap, FARSITE, Randig, and FSIM. The data are easily converted with ArcFuels scripts to the binary format (landscape file) required by the abovementioned fire models.

With the MTT approach, multiple fires are simulated to generate burn probabilities and fire behavior outputs (Figure 4). A user-defined number of random or historic based ignitions (from 1 to more than 100,000) for fixed or variable burn periods are simulated. The MTT reports a conditional burn probability at each pixel for twenty 0.5-m intervals (0–10m). The conditional burn probability is the chance that a pixel will burn at a given flame length interval, considering one ignition in the whole study area under the assumed conditions. Fireline intensity outputs are converted to flame length based on Byram's (1959) equation: the modeled intensity depends on the direction in which the fire encounters a pixel relative to the major direction of spread (i.e. heading, flanking or backing fire), as well as slope and aspect (Finney 2002). Fire size and ignition coordinates for each simulated fire are also generated as output.

Overall, three widely recognized issues with the application of the fire behavior models are the choice of the most appropriate fuel model, the quantification of canopy fuels, and the limitation of Rothermel's model in complex terrains. About the first point, several fire behavior models require a surface fuel model, which is typically chosen from standard or custom models. Fuel models are difficult to calibrate and are rarely validated with observed fire behavior (Arca *et al.* 2007; Salis 2008; Ager *et al.* 2011). Also, known limitations exist with estimates of canopy fuel characteristics, critical to model crown fire behavior (Cruz and Alexander 2010). Canopy base height and foliar moisture content are both used to calculate the critical fireline intensity, and canopy bulk density is used to determine active crown fire rate of spread. Because destructive measuring on canopy fuels is not feasible and expensive, indirect methods using tree inventory data are necessary (Reinhardt *et al.* 2006). Vegetation modeling systems such as FVS-FFE are used to process inventory data to determine the effective canopy base height and canopy bulk density using a running mean. Furthermore, fire behavior models rely on the Rothermel's surface fire equations, and fire behavior is only represented for frontal combustion. This is a limitation for wildfires spreading in complex terrains, where specific physical phenomena associated to wildfires (e.g.: fire channeling) are not properly captured by the Rothermel's spread model (Viegas and Pita 2004; Viegas 2006; Sharples *et al.* 2012).

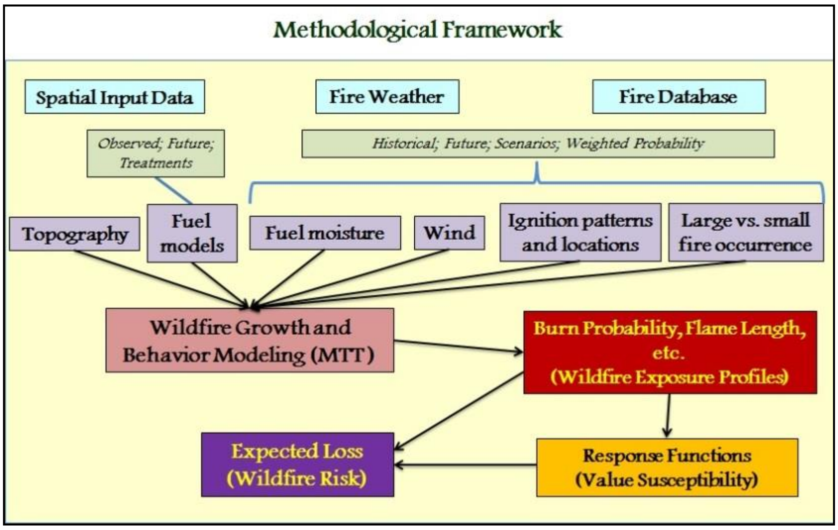


Figure 4. Methodological framework for wildfire growth and behavior modeling and wildfire risk evaluation

3. **Results**

The MTT algorithm was applied to complete several case studies in the Mediterranean Basin and in the US, as for instance 1) to quantify landscape wildfire exposure and risk, 2) to determine fire exposure profiles for values at risk, 3) to assess temporal variation in fire exposure, 4) to compare fuel treatment alternatives, and 5) to examine expected carbon offsets from fuel treatments.

In the first application, wildfire risk was calculated for northern spotted owl (*Strix occidentalis caurina*) habitat, old growth forests, and carbon in several studies in Oregon (Figure 5; Ager *et al.*

2007, 2010*a*, 2010*b*). In the first case study, the probabilistic risk analysis system was used for quantifying wildfire threats to spotted owl habitat. 10,000 wildfire simulations with randomly located ignitions were run to calculate spatially explicit probabilities of habitat loss for fuel treatment scenarios on a 70,245 ha study area. A flame length threshold for each spotted owl habitat stand was determined using FVS-FFE and used to predict the proportion of fires that resulted in habitat loss.

In later work, simulation modeling was used to analyze spatial variation in wildfire exposure on the island of Sardinia (24,000 km^2), Italy (Salis *et al.* 2013). Weather conditions associated with large escaped fires were used as input to simulate 100,000 fire events within the study area, randomly drawing from the frequency distribution of burn periods and wind directions. Historical data and wildfire simulations were used to estimate burn probabilities, flame length and fire size. Spatial patterns in modeled outputs were strongly related to fuel loadings and weather conditions, although topographic and other influences were apparent. Both studies allowed to quantify exposure profiles (burn probability, flame length, fire size) and to identify landscapes able to support large and severe fires.

In a subsequent application, the analyses were scaled up to analyze wildfire exposure factors (burn probability, fire intensity) to social and ecological values on Oregon and Washington States, and Sardinia (Italy) (Ager *et al.* 2012; Salis *et al.* 2013). Example plots of fire exposure factors can be used to identify highly valued resources at risk, and to prioritize fuel management activities.

Another application to quantify fire risk based on fire modeling was presented by Thompson *et al.* (2011), which described a quantitative, geospatial fire risk assessment tool based on burn probability modeling, identification of values at risk, and production of response functions.

In another paper, the spatiotemporal changes in wildfire exposure in Sardinia (Italy) from 1980 to 2009 in relation to historical changes in fire ignition patterns, weather, suppression activities, and land uses were analyzed (Figure 6; Salis *et al.* 2014). 100,000 fire events were simulated for two time frames, reflecting the 1980-1994 and 1995-2009 conditions, drawing from the frequency distribution of the specific burn periods and wind directions associated with large wildfires observed in the island. In that research paper, along with a net reduction in area burned and ignitions, an advance of 15 days for the fire season peak, and an increase in spring temperatures, the wildfire modeling highlighted strong spatial variations in burn probability and increments in fire exposure for WUI areas. Considering that little change was observed for land use types and associated fuels for the analyzed timeframes, a combination of social factors and suppression capabilities may be responsible of the above mentioned results.

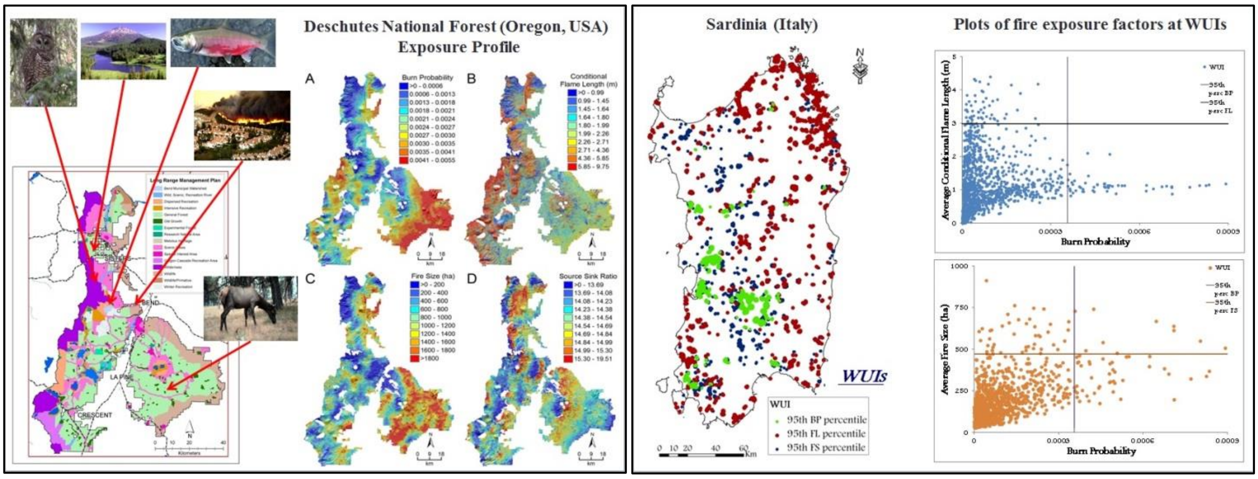


Figure 5. On the left, maps of burn probability (BP, a), conditional flame length (CFL, b), fire size (FS, c), and source sink ratio (SSR, d) for the for northern spotted owl habitat in central Oregon, US. On the right, scatterplots of fire exposure factors (BP vs CFL and BP vs FS) for wildland urban interfaces in Sardinia, Italy. The map shows the WUIs with BP, FL and FS values higher than the 95th percentile

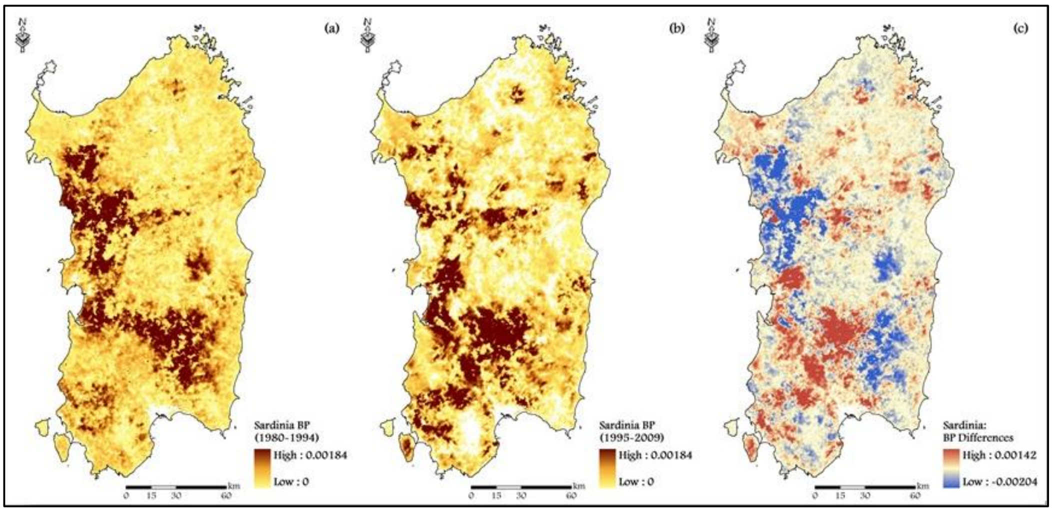


Figure 6. Variation in BP between 1995-2009 and 1980-1994 study periods in Sardinia, Italy. BP is the chance that a pixel will burn, considering one ignition in the whole study area under the assumed conditions

In another study, a risk framework was used to analyze tradeoffs between ecological management objectives (large fire resilient trees) versus the protection of residential structures in the wildland urban interface (WUI) (Figure 7; Ager *et al.* 2010*a*). The former was quantified using the expected mortality of large trees and the latter with burn probability in the location of residential structures. This study was conducted in a 16,000 ha study area in Oregon, US, to examine tradeoffs between placing fuel treatments near residential structures within an urban interface, versus treating stands in the adjacent wildlands to meet forest health and ecological restoration goals. The treatment strategies were evaluated by simulating 10,000 wildfires with random ignition locations, and replicating severe fire events based on 97th percentile historic weather conditions.

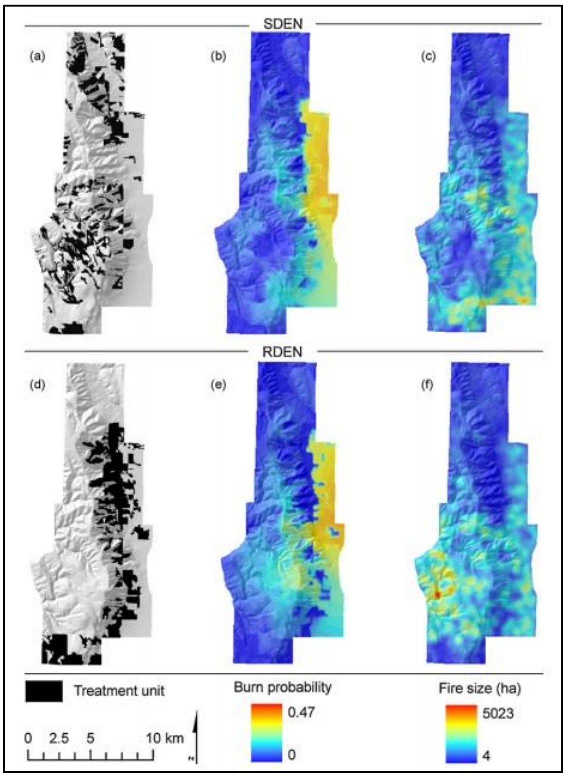


Figure 7. Maps of treatment units (a and d), burn probabilities (b and e), and kernel smoothed fire size (c and f) for the 20% treatment area for the stand density (SDEN) and the residential density (RDEN) treatment priorities, for the study area close to La Grande, OR (USA)

The main findings were that treatments strategically located on a relatively minor percentage of the landscape (10%) resulted in a roughly 70% reduction in the expected wildfire loss of large trees for the restoration scenario; treating stands near residential structures resulted in a higher expected loss of large trees, but relatively lower burn probability and flame length within structure buffers.
About mitigation activities and landscape fuel management, both positive and negative carbon impacts have been reported (Finkral and Evans 2008; Mitchell *et al.* 2009; Reinhardt and Holsinger 2010). A 70,000 ha watershed on the Fremont-Winema National Forest in southern Oregon, US, was used as case study to assess the expected carbon change from fuel treatments, combining carbon loss functions with the flame length probability outputs (Figure 8; Ager *et al*. 2010*b*). As result, a probabilistic estimate of carbon impacts that accounted for the uncertainty about future wildfire events was yielded. In this work, 30,000 wildfires were simulated with random ignition locations under both treated and untreated landscapes. The results suggested that the carbon loss from implementing fuel reduction treatments exceeded the expected carbon benefits associated with lowered burn probabilities and reduced fire severity on the treated landscape.

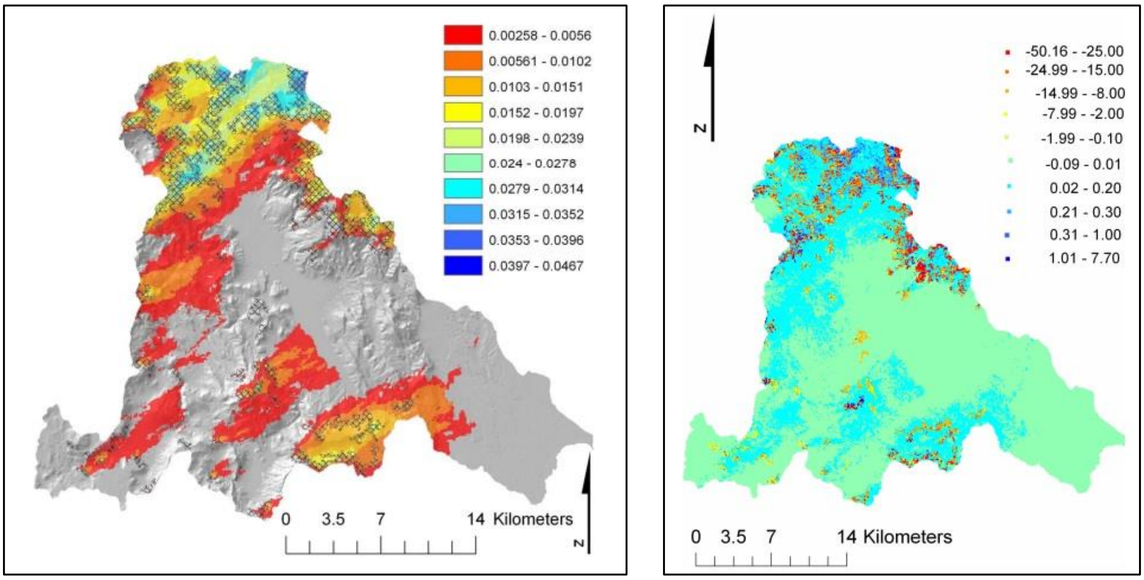


Figure 8. On the left, difference in BP between the non-treatment and treatment scenario for the Drews Creek watershed, Fremont - Winema National Forest (Oregon, USA). Stands selected for fuel treatments are hatched. Areas not shaded had differences less than 0.00258. On the right, expected carbon differences (tonnes ha^{-1}) between non-treatment and treatment scenarios

4. **Discussion and Conclusions**

Although our example applications are related to case studies from US national forests and Sardinia (Italy), the proposed methods for quantifying fire exposure and risk and for supporting fuel management planning can be applied elsewhere. When the MTT fire spread algorithm for FlamMap was parallelized for multithreaded processing, it became computationally feasible to simulate thousands of fires to generate spatially explicit fine scale burn probability and intensity maps over large areas (Ager *et al.* 2012). Extensive testing has shown that this algorithm can replicate fire size distributions in the North American ecosystems and the Mediterranean areas (Ager *et al.* 2007, 2010a, 2012; Parisien *et al.* 2007; Bar Massada *et al.* 2009; Salis *et al.* 2013, 2014). In addition, the incorporation of the MTT algorithm into fire behavior models make it feasible to rapidly generate fire exposure and risk maps for different fuel management, weather, fuel conditions, or ignition scenarios (Ager *et al.* 2011).

Newer models that use the MTT algorithm include spatiotemporal probabilities for ignition, escape, and burn conditions, and yield estimates of annual burn probabilities; the identification of the areas characterized by the highest exposure and risk, as well as the zones to be prioritized for mitigation strategies, can be easily determined with the abovementioned approach. A strong effort in the integration of tools, scientific findings and data for an operational application of the fire behavior models was addressed, with the aim of supporting wildfire risk assessment and management (Forthofer 2007; Vaillant *et al.* 2013). An important end-product is providing an efficient working environment that allows users to interact with fire behavior models in a geospatial context, and thus gain a better understanding of their limitations and biases. Application of fire behavior modeling continues to grow among planners and researchers alike, especially as land management agencies and policy makers require integrated landscape analyses (Ager *et al.* 2013). The analysis framework proposed contributes to a consistent analytical process for assessing the level of exposure and risk that communities and highly valued resources face from wildland fires. Risk provides a comprehensive index of likelihood, intensity, and potential effects. Burn probability modeling and exposure analyses play an important role in research to address a number of management problems, including analyzing carbon offsets, understanding temporal and spatial tradeoffs of fuel treatments, climate changes impacts, post fire recovery, soil erosion, and wildfire impacts to ecological conservation reserves.

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