Integrating Large Wildfire Simulation and Forest Growth Modeling for Restoration Planning

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Abstract—One of the major science gaps in U.S. wildfire policy is the lack of studies on the long-term benefits of hazardous fuel reduction and restoration programs. For instance, there is little information available to predict the impact of current fuel management and restoration on wildfire activity and whether these fuel reduction activities will meet expectations in terms of wildfire risk to social, ecological, and economic values on national forests. To address this gap, we built a new model that uses the Forest Vegetation Simulator Parallel Processing Extension and FSim large wildfire simulator model to simulate forest management on large landscapes (e.g., 1-5 million ha). We are using the model to analyze 50-year management scenarios where spatial treatment strategies and intensities are varied, and landscape response is measured in terms of future risk and avoided suppression costs. Here we present initial simulations and discuss future application of the model.

INTRODUCTION

One of the major science gaps in U.S. wildfire policy is the lack of studies on the long-term effects of hazardous fuel reduction and restoration programs. For instance, there are very few studies that predict the effects of current fuel management programs and wildfire activity through time on wildfire risk to social, ecological, and economic values on national forests. Similarly, we do not have models to test the efficacy of strategies concerning the increased use of fire for resource benefit in concert with restoration and fuel reduction programs. Part of the problem is that modeling fuel treatments to assess long-term fuel management strategies on large landscapes requires a robust forest modeling platform with the capacity to model the dynamics of fuel treatments, wildfire, and succession for individual stands (e.g., 2-20 ha) at the scale of multiple large wildfire events (e.g., 10^6 ha). There are relatively few models that have this capacity, and the respective application of these models each used a different set of assumptions and modeling approaches with respect to the various modeling components (Barros and others 2017, Conlisk and others 2015, Finney and others 2006, Loudermilk and others 2014, Millington and others 2008, Scheller and others 2011, Spies and others 2017, Syphard and others 2011). Modeling realistic fuel treatment scenarios requires simulating mechanical thinning, surface fuels mastication, piling, and prescribed fire, which are sequenced over the span of several years. Silvicultural prescriptions are tailored to individual stands based on ecological departure (Haugo and others 2015), stand structure, species composition, and fuel structure, with the objective of recreating fire resilient forests. Stand treatments must be spatially arranged within planning areas in a way that meets landscape objectives related to fire (protection versus restoration), and landscape treatment unit patterns must be replicated in terms of the size, arrangement, and dimensions of actual fuel treatment projects to correctly represent their effects on fire spread rates and intensities (Finney 2001). Equally important is correct representation of post treatment fire spread rates as well as vegetation and fuels recovery through time. The complexity of the modeling is amplified on typical Western United States landscapes that are mosaics of public, private, and private industrial ownerships, each having respective operational, legal, and economic constraints, and motivations to manage forests and fuels towards particular ecological and socioeconomic goals (Charnley and others 2015).

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Further complicating modeling issues on federal lands in the Western United States is the myriad of forest management plan constraints (Ringo and others 2015) that result in mosaics of ecological and amenity reserves on 50 to 60 percent of the forested area.

Modeling wildfire also has a number of challenges including calibration under different weather conditions and replicating spatial ignition patterns and historical fire size distributions (Finney and others 2011, Salis and others 2016). Large fires (e.g., 20 000 – 100 000 ha) in the Western United States are relatively rare events that have little or no historical precedence at the scale of a typical study area used in landscape fire modeling studies. Uncertainty regarding the effectiveness of fire suppression activities under variable weather and topography also complicates simulations (Finney and others 2009).

To further advance forest landscape simulation modeling we expanded on several previous studies by integrating the FSim large wildfire simulation model (Finney and others 2011) into the Forest Vegetation Simulator Parallel Processing Extension (FVS-PPE) and optimizing the FVS code to simulate large landscapes over time. In contrast to Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Rebain 2010), the FSim model simulates the spread and intensity of wildfire events rather than fire behavior and effects in an individual stand. We are now completing case studies in central Oregon, the Blue Mountains in eastern Oregon, and northern Idaho. In each study area we analyze a number of management scenarios in which spatial treatment strategies and intensities are varied and landscape responses are measured over 50-year simulations. Response variables include burned area and severity, wildfire impacts on the wildland urban interface, and a cost-benefit analysis of fuel treatments in terms of suppression costs. Here we describe the model and present initial simulation results as well as discuss future application.

METHODS

Model Overview

The LSim model was built by modifying the Parallel Processing Extension to FVS (FVS-PPE) (Crookston and Stage 1991) to enhance its capabilities and improve performance in areas specific to modeling wildfire and wildfire effects, then integrating the FSim wildfire simulation system with it. The model was created using FVS-PPE code downloaded in 2012. The original PPE extended FVS to allow a list of stands in a landscape to be processed one cycle at a time and makes FVS outputs available to external processes between FVS cycles. PPE can model dynamic interactions between adjacent stands, and place landscape-level constraints and goals on management activities. The utility of the program for landscape forest simulations was demonstrated in several research papers (Ager and others 2010b, Finney and others 2007). However, PPE had a number of limitations including landscape size (number of stands), processing speed, and outputs. Performance was a particular issue, with simulations of 8,000-9,000 stands (about one-fourth of a national forest) requiring several days to a week to complete.

LSim consists of a modified FVS-PPE that controls the system by calling various other components. Some of these components are available as command line programs, such as FSim (Finney and others 2010) while others were specifically developed for this simulation system and imbedded within LSim. Our modifications were built out of open FVS source code (revision 11/20/13) for FVS-PPE and the Southern Oregon and Northeast California variant of FVS (Keyser 2008). Modifications included: (1) removing the limit on the number of stands to simulate, (2) multi-threading algorithms to use multiple processors, (3) between-cycle data are now stored in RAM, rather than written to text files, (4) custom fuel model selection logic replaced default Fire and Fuels Extension to (FFE) logic, (5) a new prioritizing module that provides for multi-scale prioritization of both stands and planning areas, and (6) miscellaneous code modifications to streamline performance. The modifications made it feasible to simulate 50-year scenarios for 50,000 stands (600 000 ha) in 30 minutes. All internal FVS calculations with respect to growth, mortality, and other aspects of forest dynamics remained unchanged. These modifications make updating the base FVS code less straightforward than simply dropping in the latest version, but as updates have been made with regards to growth and yield calculations, we have incorporated those directly into the code base.

Integrating Wildfire Simulations

FSim is a widely used fire simulation model developed by Mark Finney at the Rocky Mountain Research Station (Finney and others 2011), and simulates large fire events (i.e., ignition, spread, intensity) in contrast to stand-scale fire behavior modeled in the FFE-FVS (Rebain 2010). FSim was created to simulate large numbers (e.g., 50,000) of hypothetical wildfire seasons to address a range of problems related to fire management policy in the United States. FSim employs the Minimum Time Travel (MTT) algorithm. Rates of fire spread and crown fire initiation are predicted by semi-empirical fire behavior equations (Rothermel 1972, Scott and Reinhardt 2001). FSim predicts daily probability of a fire using logistic regression with historical fire occurrence and Energy Release Component (ERC) as input variables, and fire containment using probability models also based on ERC. Weather data for fire simulations are derived from 20-30 year historical records obtained from Remote Automated Weather Stations (RAWS). The simulation operated on a daily time step and the daily probability of a fire was predicted using logistic regression with recent fire occurrence and ERC as input variables. Once a fire is ignited, the daily weather is generated using the results of a time series analysis of daily RAWS weather data (Finney and others 2011). The time series uses estimates of the seasonal trends, the autocorrelation (dependency of a day's ERC value on previous days), and the daily standard deviation to generate synthetic daily weather streams for each day of simulation. Each fire's growth and behavior were simulated from its ignition day through the remainder of the season, or until containment was achieved as predicted based on recent large fires and their recorded sequence of daily activity (Finney and others 2009). The containment model was developed from an analysis of the daily change in fire size to identify intervals of high and low spread for each fire. The containment probability model was found to be positively related to periods of low fire spread (Finney and others 2009). We assumed random ignition locations for simulated fires (Finney and others 2011). Large fire events within the study area have been primarily caused by lightning, and there are insufficient large fire incidents to detect spatial patterns if they existed. Fire simulations were performed at 270 x 270 m pixel resolution, a scale that permitted relatively fast simulation times and incorporated important spatial variation in fuel data.

Modeling Management Activities

Formulating a forest-wide restoration scenario on a typical national forest is a complex problem owing to a diversity of forest types, management objectives, and land designations. Our approach used detailed information from existing management programs on the Forest, including stand prescriptions, and a landscape scale priority scheme. The stand prescriptions were multipurpose in that they addressed both wildfire behavior and ecological departure from pre-settlement conditions. Fuel treatment prescriptions consisted of a thinning from below followed by a surface fuel reduction treatment and prescribed fire. The simulated treatment regime was specific to each of the major cover types on the Forest as determined from forest vegetation maps. The thinning from below used a threshold set by either trees per ha, stand density index, or basal area depending on the cover type. Prescribed fire parameters were chosen to replicate typical fall prescribed burning on the Forest. We modeled surface fuel reduction treatments using the FUELMOVE keyword and assumed that 90 percent of fuels between 2.54 cm and 30.48 cm in diameter were removed. The post-treatment stand characteristics in terms of fuels required by the simulation models (canopy base height, canopy height, canopy cover and canopy bulk density) were then compared to untreated characteristics for the same year to determine adjustment factors to represent canopy fuels of treated stands. This latter analysis was performed with FFE-FVS for a sample of 4,194 mapped stands using data from recent stand exams on the Forest. After discussions with local fuels planners we chose a timber-litter (TL2) fuel model (Scott and Burgan 2005) to represent treated stands.

Application

The study area was the 756 634 ha Deschutes National Forest (DNF) in central Oregon and surrounding lands contained within a 4 km buffer. The proclaimed boundary is a smoothed version of the administrative boundary that considers inholdings as part of the Forest, and thus contained extensive privately owned land (121 000 ha) and WUI (43 000 ha) in addition to the national forest land. The 4 km buffer included lands from adjacent national forests, private land, tribal entities, and the BLM. The physiographic gradients, diversity of vegetation, climate, and management resemble the setting around many national forests throughout the Western United States, and are described in detail elsewhere (Ager and others 2012). The Forest contains extensive stands of lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*) and mountain hemlock (*Tsuga mertensiana*). The Forest has experienced over 8,400 wildland fire ignitions since 1949, mostly caused by lightning during the summer months. Wildfire activity has increased over the past decade with almost 2,000 ignitions and 10 large fire events that combined burned 74 250 ha between 2002 and 2011.

We simulated nine fuel management scenarios that were comprised of three treatment intensities and three priorities. The priorities were: (1) distance to the wildland-urban interface (WUI), (2) stand basal area under 21 inches DBH (BA), and (3) potential volume mortality due to fire (PFMORT). The three treatment intensities treated 7200 ha per year, (the current treatment rate), and twice and three times that rate. The priorities were modeled at both the scale of the planning area and the individual stand. Planning areas were selected based on their overall priority score considering all stands and respective conditions within the particular planning area. For instance, under the potential volume mortality scenario, the planning area with the highest value at that point of time in the simulation was selected for treatment implementation. Treatments were then allocated to eligible stands based on the same prioritization criteria until the treatment threshold was met. We simulated a total of 30 replicates for each scenario using the South Central Oregon Variant. We compared the results for stands that were ineligible for treatment (e.g., wilderness, wild and scenic river recreation areas, research natural areas) and those eligible for treatment based on the DNF Land and Resource Management Plan described in detail in Ager and others (2012).

RESULTS

For space considerations we report here only results for the PFMORT scenario where treatments were prioritized based on potential volume mortality due to fire, estimated within FFE-FVS. Plots of burned area over time for each of the 30 replicates for the PFMORT scenario and the 1X treatment scenario show substantial variability in area burned among years and among replicates (fig. 1). High levels of inter-annual variability reflect historical patterns also shown in figure 1. The high variability in future scenarios underscores the stochastic nature of wildfire in space and time on large fire prone landscapes. Any of the replicate scenarios simulated are equally plausible wildfire futures for our study area and vary widely in terms of the amount and timing of wildfire events. Maps of fire perimeters over time in figure 2 show the spatial distribution of wildfire events for the first and last decades of one selected replicate. Fire perimeters were reasonable facsimiles of historical events within the study area.

Significant temporal trends in area burned were not detectable over the 50-year simulation for the different management intensities, meaning the combined changes in vegetation and fuels from succession and management were not sufficient to change overall fire activity within the study area for any of the three treatment levels (fig. 3). These results were obtained assuming weather consistent with historical patterns in the study area. Area burned for the treated areas (fig. 3B) did decline for the 3X treatment scenario in the initial years of the simulation, but then increased to levels equal to the 1X treatment. Area burned was slightly less for untreatable areas (fig. 3A), primarily because these areas are in higher elevation forests with long fire return intervals compared to the treatable areas. Although the outputs suggested some treatment effects and temporal trends, these differences were minor compared to variability among the replicates.

Average standing merchantable volume killed by wildfire increased over time in the untreatable areas (fig. 4A). In treatable areas volume killed by fire on a per hectare basis was more or less constant with a slight increase in year 2040. The results underscored the importance of measuring the effect of fuel management on wildfire behavior within areas that can be treated versus at the scale of national forests, where on average about 50 percent of the land

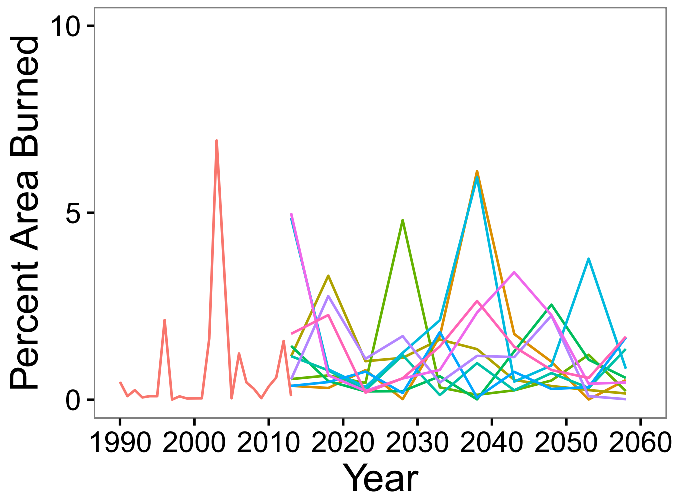

Figure 1—Area burned among 10 replicates for the scenario where treatments were prioritized based on potential fire mortality (PFMORT) under the mid-range treatment intensity (14 400 ha year^{-1}). The historical area burned is included for the same area from 1990-2012. Graph shows variability among future wildfire scenarios associated with replicate simulations.

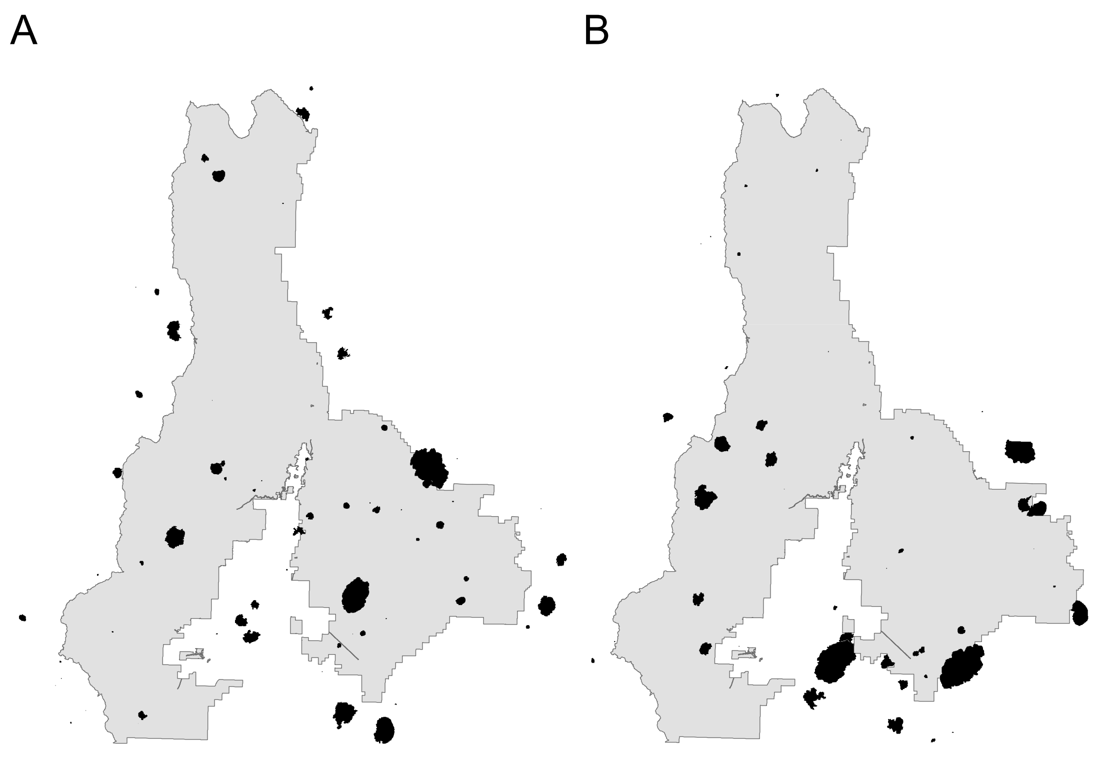

Figure 2—Fire perimeters for a single replicate for the scenario where treatments were prioritized based on potential fire mortality (PFMORT), (A) decade 1, and (B) decade 5 showing spatial variability in fire locations during the simulation.

cannot be treated due to forest planning and other legislated restrictions.

DISCUSSION

This work helps fill a gap in strategic restoration planning by providing a platform to help managers understand the long-term dynamics of forests, restoration policies, fuels, management scenarios and fire. Despite the large budget for field treatment programs in the National Forest System [$358 million per year (USDA Forest Service 2014)], and the extensive area treated [>1 million ha per year in FY2013 (USDA Forest Service 2014)], decision support tools to understand the landscape-scale effectiveness of fuel treatment programs and their synergistic effect on succession over the long term do not exist. This modeling system can be used to test the long-term effectiveness of accelerated restoration policies and programs to build fire resilient landscapes on national forests. The fine spatiotemporal scale of the modeling system provides a robust and high resolution platform to analyze fuel treatment strategies on landscapes that are highly fragmented and variable with respect to constraints on mechanical treatments, vegetation, fuels, ownership and weather. In particular, we advanced forest landscape succession and disturbance modeling by integrating a widely applied mechanistic wildfire simulation system with a forest growth simulator that has been calibrated for a wide range of forest ecosystems. The fire modeling system builds an important bridge between forest planning efforts on national forests

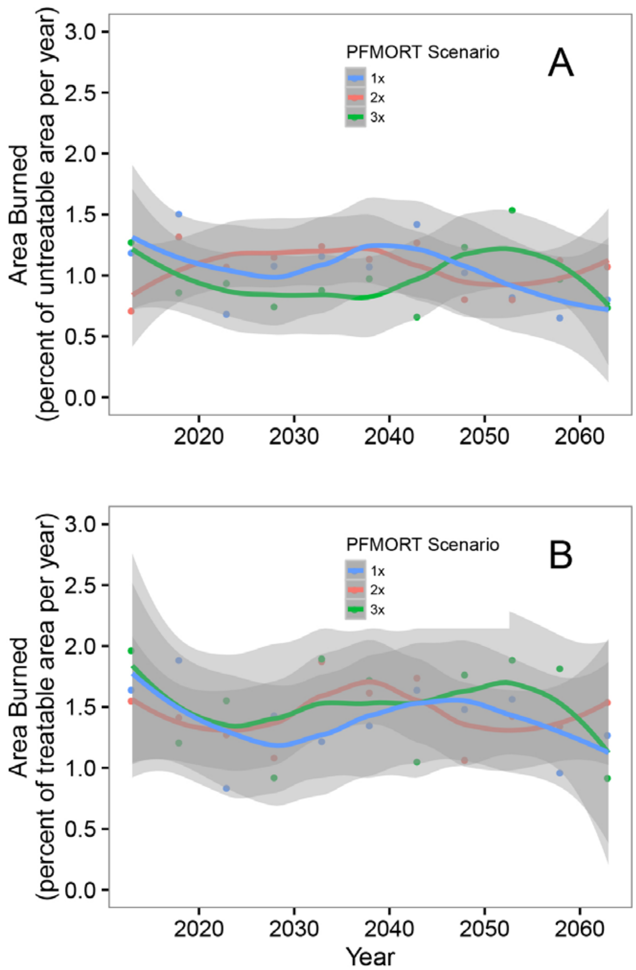

Figure 3—Average annual area burned for the scenario where treatments were prioritized based on potential fire mortality (PFMORT). (A) stands ineligible for treatment (e.g., wilderness); (B) stands that are eligible for treatment based on the Deschutes National Forest Plan. Data are averaged over 30 replicate simulations.

and the fire management programs that use the FlamMap fire behavior library.

FVS-PPE has been used in several previous studies, but none of these incorporated wildfire as an endogenous process within the simulation system. In a previous study in eastern Oregon, the PPE was used to model spatial fuel treatment scenarios that targeted either restoration of upland forest or crown fire in and around urban interface (Ager and others 2010b). In another study the PPE was used to analyze landscape carbon budgets from fuel management (Ager and others 2010a). The PPE was also used by Finney and others (2007) in a detailed temporal landscape modeling study of fuel treatment optimization, but that study did not incorporate wildfire as an endogenous process within the simulation system.

The FSim model and underlying FlamMap code library are widely used for strategic fuels planning and risk assessment in the United States (Thompson and others 2011). The MTT algorithm and associated wrappers are a core component of United States wildfire planning systems (Ager and others 2014, Ager and others 2011, Andrews 2007, Finney and others 2011, Noonan-Wright and others 2011, Rollins 2009, Scott and Burgan 2005) and are used globally in other fire prone systems as well (Alcasena and others 2015, Kalabokidis and others 2015, Oliveira and others 2016, Salis and others 2014). Thus as part of this work we leverage the long history of fire model development in United States federal land management agencies (Systems for Environmental Management 2017).

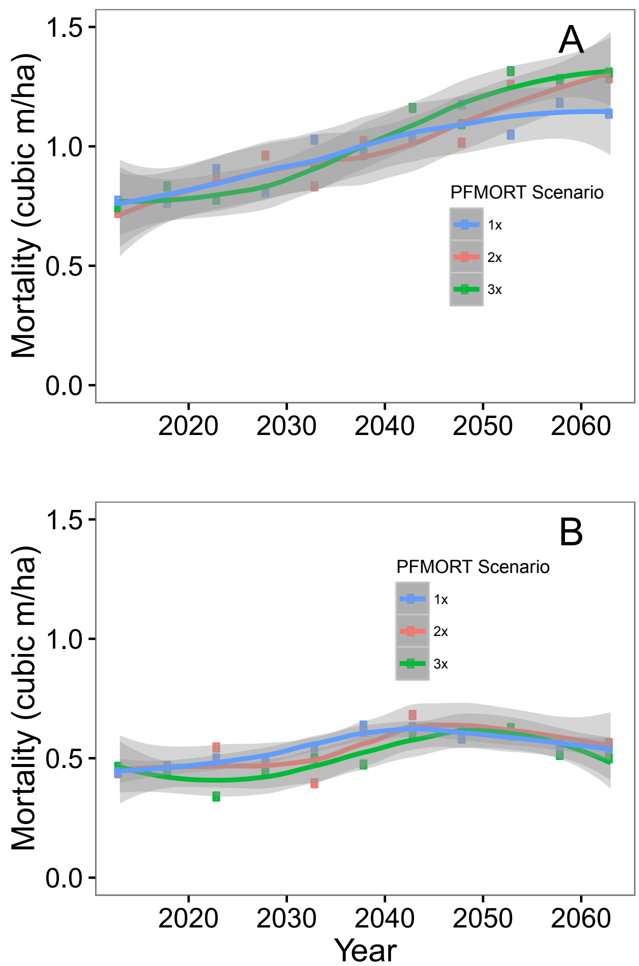

Figure 4—Stand mortality from wildfire. (A) stands ineligible for treatment (e.g., wilderness); (B) stands that are eligible for treatment based on the Deschutes National Forest Plan. Data are averaged over 30 replicate simulations.

The focus of the current paper was describing methodologies for building LSim. Our simulation experiment was primarily conducted to demonstrate the system in concert with the modeling methods and wildfire prediction system. Additional simulation studies will be reported in later communications. The simulations we presented suggest that under assumptions of constant climate wildfire trends under current levels of management are stable. Substantial successional induced changes in surface and canopy fuels are not predicted for the study landscape. This suggests that the system is not at a specific tipping point with respect to fuels accumulation and that the current rate of treating fuels as part of ecological restoration programs (Buford and others 2015, Noss and others 2006) is about the same as fuels accretion. Analysis of variability among years for future wildfire scenarios suggested that extreme fire behavior may or may not be realized in the near term future (e.g., 1–10 years). High variation among years (and replicates),where each represent an alternative future scenario, suggests that management policies may or may not be perceived in the short run as making a significant difference in fire activity. This variability has manifold effects on policy implementation by obscuring trends in wildfire activity in response to restoration and protection programs, and further complicating the assessment of restoration programs and their potential benefits.

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REFERENCES

Ager, A.A.; Day, M.A.; McHugh, C.W. [and others]. 2014. Wildfire exposure and fuel management on Western U.S. national forests. Journal of Environmental Management. 145: 54-70.

Ager, A.A.; Finney, M.A.; McMahan, A.J. [and others]. 2010a. Measuring the effect of fuel treatments on forest carbon using landscape risk analysis. Natural Hazards and Earth System Sciences. 10: 2515-2526.

Ager, A.A.; Vaillant, N.M.; Finney, M.A. 2010b. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. Forest Ecology and Management. 259: 1556-1570.

Ager, A.A.; Vaillant, N.M.; Finney, M.A. 2011. Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. Journal of Combustion. 572452: 19. http://dx.doi.org/10.1155/2011/572452. [Date accessed: February 2017].

Ager, A.A.; Vaillant, N.M.; Finney, M.A. [and others]. 2012. Analyzing wildfire exposure and source–sink relationships on a fire prone forest landscape. Forest Ecology and Management. 267: 271-283.

Alcasena, F.J.; Salis, M.; Ager, A.A. [and others]. 2015. Assessing landscape scale wildfire exposure for highly valued resources in a Mediterranean area. Environmental Management. 55: 1200-1216.

Andrews, P.L. 2007. BehavePlus fire modeling system: past, present, and future. In: Proceedings of 7th Symposium on Fire and Forest Meteorology. Bar Harbor, ME: American Meteorological Society: 13.

Barros, A.; Ager, A.A.; Day, M.A. [and others]. 2017. Spatiotemporal dynamics of simulated wildfire, forest management and forest succession in central Oregon, U.S.A. Ecology and Society. 22(1): 24.

Buford, M.; Chan, C.; Crockett, J. [and others]. 2015. From accelerating restoration to creating and maintaining resilient landscapes and communities across the nation: update on progress from 2012. FS-1069. U.S. Department of Agriculture Forest Service. 26 p.

Charnley, S.; Poe, M.R.; Ager, A.A. [and others]. 2015. A burning problem: social dynamics of disaster risk reduction through wildfire management. Human Organization. 74: 329-340.

Conlisk, E.; Syphard, A.D.; Franklin, J. [and others]. 2015. Predicting the impact of fire on a vulnerable multi-species community using a dynamic vegetation model. Ecological Modelling. 301: 27-39.

Crookston, N.L.; Stage, A.R. 1991. User’s guide to the parallel processing extension of the prognosis model. Gen. Tech. Rep. INT-281. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Research Station. 93 p.

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.; Grenfell, I.C.; McHugh, C.W. 2009. Modeling containment of large wildfires using generalized linear mixed model analysis. Forest Science. 55: 249-255.

Finney, M.A.; McHugh, C.W.; Grenfell, I.C. [and others]. 2010. Continental-scale simulation of burn probabilities, flame lengths, and fire size distributions for the United States. In: D. Viegas ed., Proceedings of the VI International Conference on Forest Fire Research. Coimbra, Portugal: University of Coimbra: 12.

Finney, M.A.; McHugh, C.W.; Grenfell, I.C. [and others]. 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment. 25: 973–1000.

Finney, M.A.; Seli, R.C.; McHugh, C.W. [and others]. 2006. Simulation of long-term landscape-level fuel treatment effects on large wildfires. In: Andrews, P.L.; Butler, B.W., ed. Fuels Management-How to Measure Success. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station: 125-147.

Finney, M.A.; Seli, R.C.; McHugh, C.W. [and others]. 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. International Journal of Wildland Fire. 16: 712-727.

Haugo, R.; Zanger, C.; DeMeo, T. [and others]. 2015. A new approach to evaluate forest structure restoration needs across Oregon and Washington, USA. Forest Ecology and Management. 335: 37-50.

Kalabokidis, K.; Palaiologou, P.; Gerasopoulos, E. [and others]. 2015. Effect of climate change projections on forest fire behavior and values-at-risk in southwestern Greece. Forests. 6: 2214-2240.

Keyser, C.E. 2008. South Central Oregon and Northeast Califrnia (SO) Variant Overview-Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: USDA Forest Service, Forest Management Service Center. 74 p.

Loudermilk, E.L.; Stanton, A.; Scheller, R.M. [and others]. 2014. Effectiveness of fuel treatments for mitigating wildfire risk and sequestering forest carbon: A case study in the Lake Tahoe Basin. Forest Ecology and Management. 323: 114-125.

Millington, J.D.A.; Romero-Calcerrada, R.; Wainwright, J. [and others]. 2008. An agent-based model of Mediterranean agricultural land-use/cover change for examining wildfire risk. Journal of Artificial Societies and Social Simulation. 11(44): 4. http://jasss.soc.surrey.ac.uk/11/4/4.html. [Date accessed: January 2017].

Noonan-Wright, E.K.; Opperman, T.S.; Finney, M.A. [and others]. 2011. Developing the U.S. Wildland Fire Decision Support System. Journal of Combustion. 168473: 14. http://dx.doi.org/10.1155/2011/168473. [Date accessed: January 2017].

Noss, R.F.; Franklin, J.F.; Baker, W.L. [and others]. 2006. Managing fire-prone forests in the Western United States. Frontiers in Ecology and the Environment. 4: 481-487.

Oliveira, T.M.; Barros, A.M.G.; Ager, A.A. [and others]. 2016. Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission. International Journal of Wildland Fire. 25: 619-632.

Rebain, S.A. 2010. The fire and fuels extension to the forest vegetation simulator: updated model documentation. Internal Report. 396 p. On file with: U.S. Department of Agriculture Forest Service, Forest Management Service Center, Fort Collins, CO 80528.

Ringo, C.; Ager, A.A.; Day, M.A. [and others]. 2015. A spatial database for restoration management capability on national forests in the Pacific Northwest USA. Gen. Tech. Rep. PNW-GTR-919. Portland, OR: U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station. 80 p.

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

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Salis, M.; Ager, A.A.; Arca, B. [and others]. 2014. Analyzing wildfire exposure on Sardnia, Italy. Geophysical Research Abstracts. 16: EGU2014-11596.

Salis, M.; Arca, B.; Alcasena, F. [and others]. 2016. Predicting wildfire spread and behaviour in Mediterranean landscapes. International Journal of Wildland Fire. 25: 1015-1032.

Scheller, R.M.; Spencer, W.D.; Rustigian-Romsos, H. [and others]. 2011. Using stochastic simulation to evaluate competing risks of wildfires and fuels management on an isolated forest carnivore. Landscape Ecology. 26: 1491-1504.

Scott, J.H.; Burgan, R.E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station. 72 p.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station. 59 p.

Spies, T.; White, E.; Ager, A. [and others]. 2017. Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. Ecology and Society. 22(1): 25.

Syphard, A.D.; Scheller, R.M.; Ward, B.C. [and others]. 2011. Simulating landscape-scale effects of fuels treatments in the Sierra Nevada, California, USA. International Journal of Wildland Fire. 20: 364-383.

Systems for Environmental Management. 2017. Public domain software for the Wildland Fire Community. www.fire.org. [Date accessed: May 2017].

Thompson, M.; Calkin, D.; Gilbertson-Day, J. [and others]. 2011. Advancing effects analysis for integrated, large-scale wildfire risk assessment. Environmental Monitoring and Assessment. 179: 217-239.

USDA Forest Service. 2014. Fiscal year 2015 budget justification. Internal Report. On file with: U.S. Department of Agriculture Forest Service, Washington, DC 20250.