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Wildfire exposure and fuel management on western US national forests

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ABSTRACT

Substantial investments in fuel management activities on national forests in the western US are part of a national strategy to reduce human and ecological losses from catastrophic wildfire and create fire resilient landscapes. Prioritizing these investments within and among national forests remains a challenge, partly because a comprehensive assessment that establishes the current wildfire risk and exposure does not exist, making it difficult to identify national priorities and target specific areas for fuel management. To gain a broader understanding of wildfire exposure in the national forest system, we analyzed an array of simulated and empirical data on wildfire activity and fuel treatment investments on the 82 western US national forests. We first summarized recent fire data to examine variation among the Forests in ignition frequency and burned area in relation to investments in fuel reduction treatments. We then used simulation modeling to analyze fine-scale spatial variation in burn probability and intensity. We also estimated the probability of a mega-fire event on each of the Forests, and the transmission of fires ignited on national forests to the surrounding urban interface. The analysis showed a good correspondence between recent area burned and predictions from the simulation models. The modeling also illustrated the magnitude of the variation in both burn probability and intensity among and within Forests. Simulated burn probabilities in most instances were lower than historical, reflecting fire exclusion on many national forests. Simulated wildfire transmission from national forests to the urban interface was highly variable among the Forests. We discuss how the results of the study can be used to prioritize investments in hazardous fuel reduction within a comprehensive multi-scale risk management framework.

1. Introduction

The growing incidence of catastrophic fires in the US and elsewhere is forcing public land management agencies and private landowners to re-examine strategies to reduce human and ecological losses (USDA Forest Service, 2010). Mega-fires in the western US (Williams, 2013) overwhelm suppression efforts and burn through large areas of wildlands, destroying infrastructure and homes, and damaging scenic and ecological values. These trends continue despite significant changes in wildland fire policies, including the National Fire Plan, Healthy Forest Restoration Act (HFRA) and most recently, the Federal Land Assistance, Management and Enhancement Act (FLAME, USDA-USDI, 2014) that call for strategic investments in fuel management, wildfire preparedness, and suppression. For federal land management agencies such as the USDA Forest Service, this sequence of legislation has provided a moving window of policy direction for the national forest system (henceforth NFS) faced with a growing suppression budget and the task of reducing risk to people and minimizing adverse wildfire impacts to an array of ecosystem services. Implementing these policies has required prioritizing funding to the 155 national forests and grasslands, and downscaling the policy intent to field units where site-specific fuel treatment projects are designed and

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implemented. The annual budget for these activities within the NFS is between 200 and 300 million USD (USDA, 2012), resulting in treatments on an average area of 1.0 million ha per year between 2002 and 2011 (USDA Forest Service, 2011b). A substantial portion of the budget and treatment area is targeted to the wildland urban interface (WUI), where for instance, between 2004 and 2008 some 45% of the investments were made (USDA Forest Service, 2011a).

Despite many demonstrated instances where Forest Service fuel management projects have reduced fire severity and facilitated suppression efforts (Safford et al., 2012; USDA-USDI, 2014), the program has been critically reviewed by oversight agencies (GAO, 2007). This is not surprising given that predicting the effects of fuel modifications on risk posed by future, highly stochastic and large (e.g., 100,000 ha) wildfire events is a complex problem. While a growing body of literature has advocated increased use of risk science and risk assessment methods to cope with uncertainty issues (GAO, 2004, 2009; Miller and Ager, 2012), developing consistent and standardized performance metrics for field implementation is a complex process. However, without formal risk-based protocols and assessments, it is not possible to track changes in risk from fuel management programs designed to reduce it. At the same time, developing a standardized measure of wildfire risk across 155 US national forests, each having unique ecological settings and social context, is a challenging and perhaps intractable problem.

In this paper we draw on a number of empirical and modeled data sources to systematically describe variation in wildfire exposure among the fire prone national forests in the western US with the broad goal of creating a strategic understanding of how wildfire potentially impacts each of the Forests, and how those impacts are related to current investment in federal fuel management programs. Wildfire exposure concerns the general description of potential wildfire activity in relation to values of concern, and is a precursor to more detailed risk analyses where losses are predicted with associated probabilities (Finney, 2005). Exposure analyses are a necessary step in risk assessments and typically reveal much of the same spatial patterns without the complexity of predicting fire effects on specific human and ecological values. Our exposure analysis mined data from historical records and used simulation modeling to examine five interrelated questions that all have a direct bearing on fuel management strategies aimed at reducing risk on the western national forests: 1) what is the relative magnitude in wildfire exposure both within and among the Forests, 2) what are the major trends among pre-settlement, recent, and simulated fire activity in terms of burned area, 3) to what extent do wildfires ignited within the NFS contribute to wildfire exposure to surrounding lands and the wildland urban interface (WUI), 4) what is the future probability for a “mega fire” event in each of the Forests, and 5) how do recent fuel management investments among the national forests compare with recent burned area? We used the outputs from the above analyses to rank the national forests for selected exposure metrics to illustrate the magnitude of the differences and understand regional trends. Finally, we discuss potential improvements to the current budget allocation process for the fuel treatment program within the NFS, and propose a long-term goal of developing an adaptive risk protocol that connects funding priorities with monitoring activities to fine tune fuel management investments in relation to their performance in terms of reducing risk.

2. Methods

2.1. Study area

The study area included the 82 national forests, grasslands, and scenic areas west of the Mississippi River (henceforth Forests, Fig. 1, Sup-Table 1), and the adjacent wildland urban interface (WUI) as mapped by the SILVIS project (Radeloff et al., 2005). The Forests cover over 67 million ha and contain a diverse array of forest and rangeland ecosystems. About 64 million ha are classified as burnable from LANDFIRE data (Rollins, 2009). The Forest network is dissected by many mountain ranges including the Rockies, Sierra Nevada, Cascade, and numerous sub-ranges creating pronounced gradients in vegetation, climate, and fire regimes.

2.2. WUI boundaries

The SILVIS polygon-based spatial data (Radeloff et al., 2005) were used to create a WUI layer to examine exposure to private property adjacent to Forests as described below. We removed polygons that had 1) less than 50% vegetation, thus very low levels of wildfire spread and severity; 2) low population density (<6.17 housing units km^{-2}), with lower concern of transmission; and 3) polygons <100 ha in size due to the scale of the simulation data. Each polygon was subsequently assigned to the nearest Forest based on the distance from the WUI centroid to the Forest boundary. The selection of thresholds to remove polygons preserved the larger, higher density WUI areas around Forests, and created a layer that was more suitable for large scale comparisons of exposure across the Forests included in the study.

2.3. Recent fire occurrence data

We obtained a recent fire history (1992–2009) database that was developed for fire simulation research (Finney et al., 2011) from federal and state agency fire suppression records (Short, 2013). The data consisted of ignition location and date, final fire size, and a number of other attributes and were initially derived from the National Interagency Fire Management Integrated Database (NFMID) at the National Information Technology Center in Kansas City, Missouri (accessed 11/14/2011). The data extracted covered wildfires over the period 1992–2009 and provided information on the size and ignition location of approximately 130,000 fires for the 82 western Forests. Of those, approximately 91% of fires were reported as originating on Forest lands with federal protection responsibility. After initiating the study, we re-queried the NFMID database to specifically obtain attributes not included in the Short (2013) database pertaining to the percent of different ownerships burned by individual wildfires. These latter data were required for analysis of empirical transmission as described below, and spanned the time period 1990–2011 (FIRESTAT, 2011).

2.4. Fuel investment data

Data on fuel treatment budgets for the Forests were obtained from administrative reports as compiled by Fire and Aviation Management in the USFS Pacific Northwest Region office in Portland, Oregon (L Mayer, Region 6 Forest Service Fuel Planner). The data consisted of hazardous fuels (Forest Service budget code WFHF) allocations to individual Forests over the period 2006–2011. We adjusted allocations for inflation using the 2009 annual average from the Consumer Price Index (ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt) and used the budget data to compare total fuel investments to recent and simulated fire occurrence. The data were adjusted on a Forest by Forest basis to remove allocations to Forests that were contained within the hazardous fuels budget but not targeted for fuels projects. The budget allocation to each Forest was the outcome of national and regional funding processes within the agency and broadly represents fuel management priorities at the scale of individual Forests.

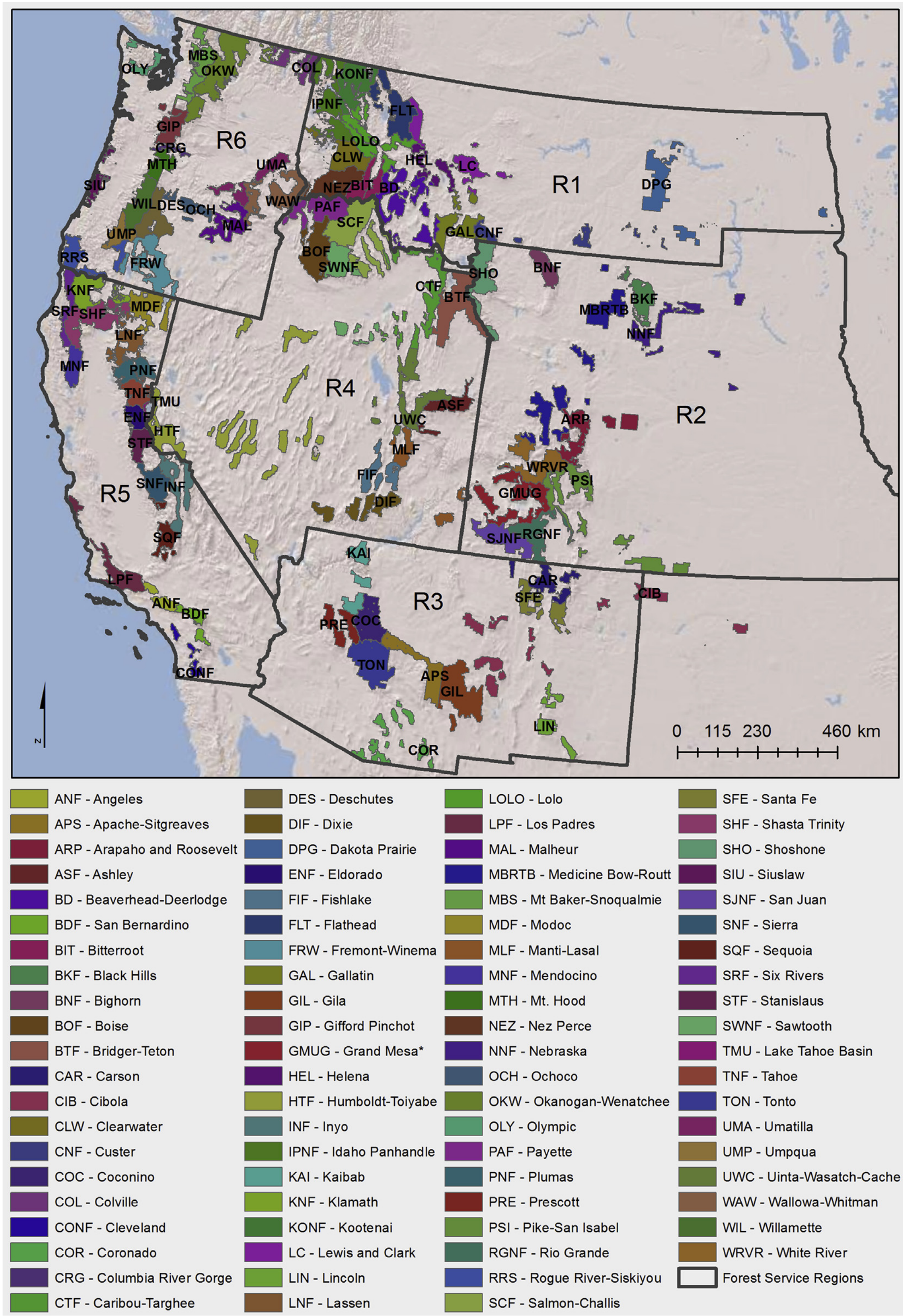

Fig. 1. Map of the 82 national forests in the western US included in the study. Black lines denote Forest Service administrative regional boundaries among the six western regions.

2.5. Pre-European settlement fire return interval data

We obtained pre-European settlement (hereafter pre-settlement) mean fire return interval (MFRI) data from LANDFIRE (2013b). The Mean Fire Return Interval (MFRI) layer quantifies the average period between fires under the presumed historical fire regime (LANDFIRE, 2013b). MFRI is estimated and mapped using the Vegetation and Disturbance Dynamics (VDDT) model, LANDFIRE Biophysical Settings (BPS) data, and the LANDFIRE Refresh Model Tracker data. The MFRI data are classified into 22 categories of return intervals ranging from a minimum of 0–5 years, to a maximum of >1000 years. The reciprocal of these intervals is the estimated pre-settlement burn probability (McHugh and Finney, Unpublished results).

2.6. LandScan population data

LandScan (2009) population data were used to populate the WUI layer described above. LandScan data represent the finest resolution global population distribution data at a 1 km resolution (Bhaduri et al., 2007). The data are modeled population and represent an ambient population (average over 24 h). The data are used as a surrogate for structures and offer a finer scale and continuous data source to analyze structure density within WUI polygons compared to the census data in the SILVIS layer. Each WUI polygon was assigned the sum of the population count for all the LandScan pixels contained within it.

2.7. Wildfire simulation modeling

Wildfire simulation data from the large fire simulator FSIM (Finney et al., 2011) were used to quantify the current wildfire exposure within and among the Forests. The simulations were completed as part of the federal wildfire planning effort Fire Program Analysis (FPA, 2010). The simulation methods are reported elsewhere in detail (Finney et al., 2011) and the results have been used in a number of other studies (Ager et al., 2012a; Thompson et al., 2011). Briefly, FSIM generates daily wildfire scenarios for a large number of hypothetical wildfire seasons using relationships between historical Energy Release Component (ERC, Bradshaw et al., 1984) and historical fire occurrence. Wildfires are then simulated using the minimum travel time (MTT, Finney, 2002) fire spread algorithm under weather conditions derived from time series analysis of historical weather. The latter are derived from the network of remote automated weather stations located throughout the US (Zachariassen et al., 2003).

FSIM outputs consist of 1) the overall burn probability (BP), 2) the probability of a pixel burning at six different flame length classes (BP_i), 3) a fire list file with the size (ha) and ignition location of each fire, and 4) fire perimeters in a GIS polygon file. The BP for a given pixel is an estimate of the annual likelihood that a pixel will burn given a random ignition within the study area. Fire intensity (Byram, 1959) is predicted by the MTT algorithm and is dependent on the direction 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). FSIM converts fireline intensity (FI, kW m^{-1}) to flame length (FL, m) based on Byram's (1959) equation:

$$\mathrm{FL} = 0.775(\mathrm{FI})^{0.46} \tag{1}$$

The flame length distribution generated from multiple fires burning each pixel was used to calculate the conditional flame length (CFL):

$$\mathrm{CFL} = \sum_{i=1}^{6} (\mathrm{BP}_i/\mathrm{BP})(\mathrm{FL}_i) \tag{2}$$

where FL_i is the flame length midpoint of the ith category, and BP_i is the probability of fire in flame length i. Conditional flame length is the probability-weighted flame length given a fire occurs and is a measure of wildfire hazard (Ager et al., 2010).

We also calculated the simulated annual area burned at high intensity (ABHI) as

$$\mathrm{ABHI} = (\mathrm{BP}_{>2.4\ \mathrm{m}})(\mathrm{Area}) \tag{3}$$

where $BP_{>2.4m}$ is the annual probability of a fire with >2.4 m flame length (categories five and six from FSIM). ABHI estimated the proportion of area exposed to high intensity fire on an annual basis. Our choice of 2.4 m as a flame length threshold was based on a number of factors, including previous research building fire-effects loss functions (Ager et al., 2010). For instance, flame lengths >2.4 m will generally result in significant torching, crown fire activity, and tree mortality in mixed conifer forests. A complete loss of key features such as northern spotted owl habitat, old growth forest, and fire sensitive plant species would generally be expected. In addition, fire protection efforts for key features are compromised since direct ground attack on a fire perimeter is not attempted at or above this threshold.

The data used in the current study consisted of 1,332,139 ignitions that represented between 20,000 and 50,000 fire season replicates on each of the Forests (see Finney et al., 2011).

2.8. Analyses

The bulk of the analyses consisted of graphical examination of the variation among Forests in pre-settlement, recent (1992–2009), and simulated fire occurrence and resulting exposure. Scatterplots and box plots of key FSIM model outputs and derived variables were summarized for each Forest. We used the data on recent fire activity to summarize burned area and fire occurrence as a function of fire size and ignition frequency by Forest. We calculated the recent annual percent area burned as a proportion of the total burnable area. The burnable area was determined from LANDFIRE fuel model data (Rollins and Frame, 2006) by removing urban, snow/ice, agriculture, water, and barren fuel types.

Fire transmission from Forests to adjacent land for the recent fire record was calculated from the NFMID database described previously. The database contains an estimate of the proportion of the area burned in different ownership categories for each fire, which was used to calculate the area burned around Forests by fires that ignited within them. We did not differentiate between the different types of non-NFS lands that received fires from NFS lands.

More detailed analysis of fire transmission specifically to adjacent WUIs was completed using the simulation outputs. Specifically we intersected wildfire perimeters for fires ignited on the NFS with the SILVIS WUI layer described above, and then calculated the area of WUI burned by each fire perimeter. We also calculated the population exposed by each fire perimeter as the product of the LandScan population estimate within each WUI polygon and the proportion of the WUI polygon burned (see Section 2.6). Individual SILVIS WUI polygons were assigned to the closest NF.

To examine the probability of future mega-fires on each Forest we used the FSIM fire list outputs to estimate fire size probability distributions. The FSIM fire lists contain the ignition location and fire size (ha) of each simulated fire which can be summarized to calculate fire frequency (probability) versus fire size. The simulations are stratified according to Fire Planning Units (FPUs, Short, 2013). For the eight Forests that spanned multiple FPUs we calculated mega-fire probability based on the FPU with the largest portion of Forest area. This resulted in excluding simulations for particular areas within specific Forests, such that the simulations represented on average 61% of the area within the Forests. These outputs were then compared to the recent fire history to examine the likelihood of a simulated fire event that substantially (2–3 times) exceeded previously observed large fire events on particular Forests.

We compared pre-settlement, recent, and simulated wildfire activity to examine changes in fire regime on individual Forests. Recent and simulated area burned were compared to understand how FSIM outputs reflected empirical data on fire activity (see also

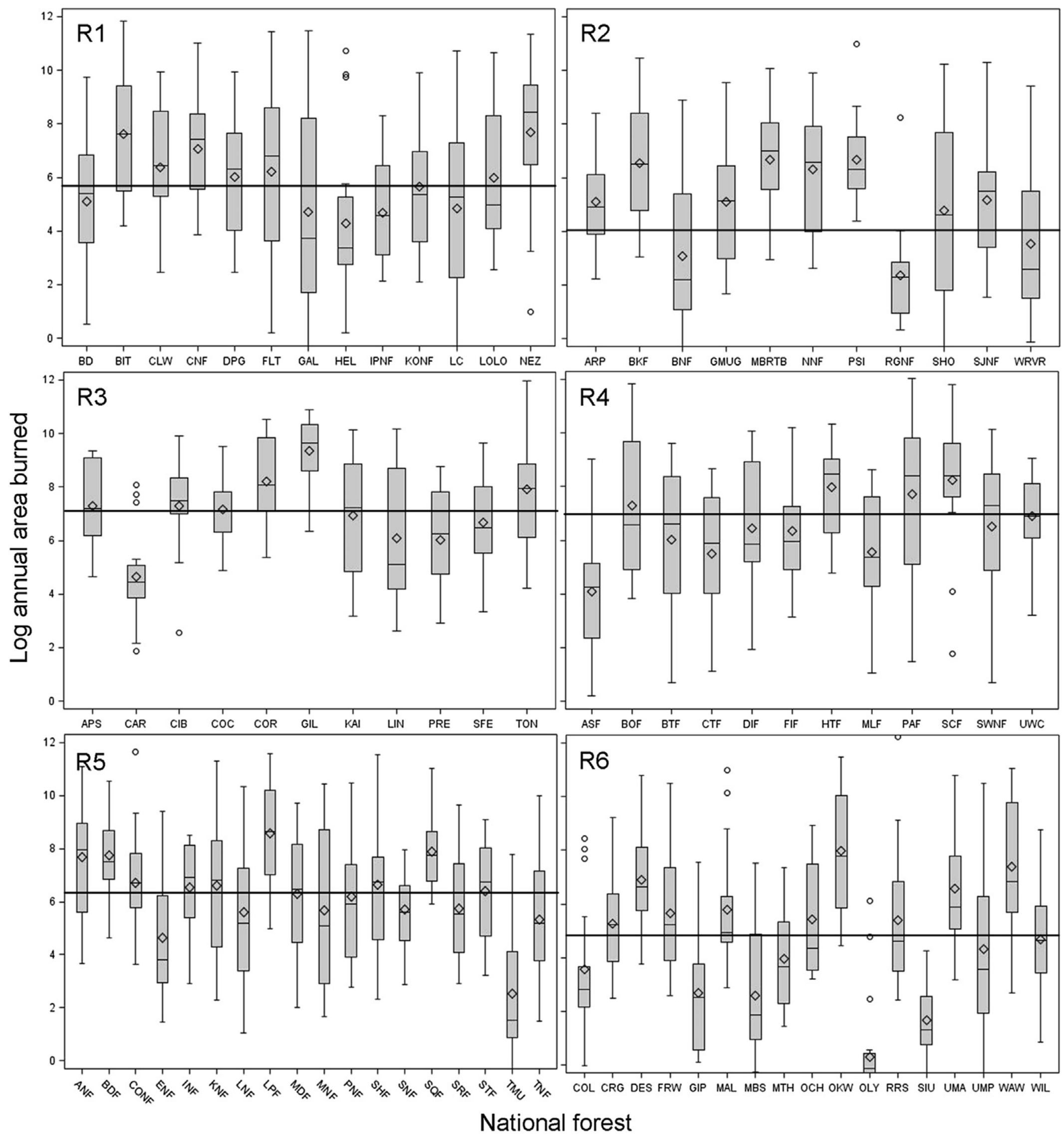

Fig. 2. Box plots of log transformed annual area burned on the 82 national forests in the western US grouped by US Forest Service region. Diamonds indicate Forest means; thick black horizontal line indicates regional average. Data are from Short (2013) for the period 1992–2009. Note that fires that burned onto a Forest from ignitions outside the Forest boundary were not included in the calculations.

Finney et al., 2011). We then calculated the ratio of the pre-settlement burn probability calculated from MFRI (see above) to the simulated burn probability to examine how burn probability compared between pre-settlement and simulated conditions. The MFRI data were also converted to annual area burned and then compared with simulated area burned to examine and map change in the pre-settlement fire regimes.

While the analyses described above provided detailed information at the scale of individual national forests, an assessment of variation within (versus among) Forests can also inform fuel management priorities at the sub-Forest scale. Therefore, we summarized exposure for each 12-digit hydrologic unit code watershed (henceforth HUC6) that are used by many national forests as a land unit for prioritizing fuel management and restoration activities (USDA Forest Service, 2011b), and by researchers to develop prioritization schemes (Gartner et al., 2008; Hessburg et al., 2007). HUC6 watersheds range from 1000 to 40,000 ha (mean = 7700 ha). Exposure was represented by BP and CFL, averaged for each HUC6, and displayed as scatterplots to show the relative variation within and among Forests.

Finally, to rank the Forests with respect to simulated wildfire exposure, we calculated the proportional contribution of each Forest to each of the six metrics derived from the wildfire simulations: 1) ABHI, 2) count of subwatershed exposure based on both BP and CFL in the 75th percentile, 3) probability of a mega-fire greater than 20,000 ha, 4) area of WUI burned by simulated fires ignited on NFS lands, 5) simulated population exposure, and 6) mean departure from MFRI based on simulated burn probability. Although many other factors could be considered for inclusion in a ranking scheme, the metrics we used captured important aspects of potential fire exposure in terms of prioritizing fuel management activities.

3. Results

3.1. Variation in recent wildfire exposure

The comparative analysis of wildfire exposure among the 82 Forests showed substantial variation both within and among regions (Figs. 2–4 and Figs. 6–10). The results are not surprising since the Forests vary significantly in size and are located on a wide range of physiographic conditions. However, much of the variation was not size related, and furthermore, the historical data suggest important differences in fire regimes in terms of fire frequency versus size. The highest regional average for annual area burned was Region 4, at 7929 ha yr^{-1} (Sup-Table 2). Box plots (Figs. 2 and 3) of annual area burned and average fire size show significant differences among Forests within regions. Annual area burned between 1992 and 2009 ranged from a low of 12 ha (Siuslaw) to a high of 29,274 ha (Payette). The Intermountain Region (R4) had the two highest average annual area burned values for an individual Forest (Payette and Boise), followed by the Pacific Southwest (R5) and Southwest regions (R3). For the latter two Regions, the specific forests that had the highest average annual area burned values were the Los Padres and the Gila.

Regional variation in the average fire size was minimal, especially compared to variation among Forests (Fig. 3). Most of the area burned was from fires in the 1000–10,000 range for Regions 1, 2 and 3, and in the 10,000–50,000 ha range for all remaining regions (data not shown). Comparing Figs. 2 and 3 shows whether the variation in annual area burned within regions was caused by relatively few, large fires, versus more frequent smaller fires. For instance, in Region 3, the Carson (CAR, second from left) exhibited below average annual area burned, and had relatively few, large fires, compared to many of the other Forests in the region. By contrast, the Gila (GIL, Figs. 2 and 3, middle R3 panel) had a significantly higher annual area burned caused by a larger number of fires of average size. Variation among Forests in fire number was also pronounced within regions, as indicated by the width of the box in Fig. 3. Coefficient of variation among Forests within region in average fire size varied from a low of 47% (R3) to a high of 170% (R6, Sup-Table 2).

The relationship between ignition frequency and burned area (Fig. 4A) showed that some Forests had relatively large area burned with relatively low number of ignitions (e.g., Payette) while others had a large number of ignitions, but relatively low area burned (e.g., Coconino) and small fire size. On a per area basis (Fig. 4B) wide variation was observed among Forests within a region, although

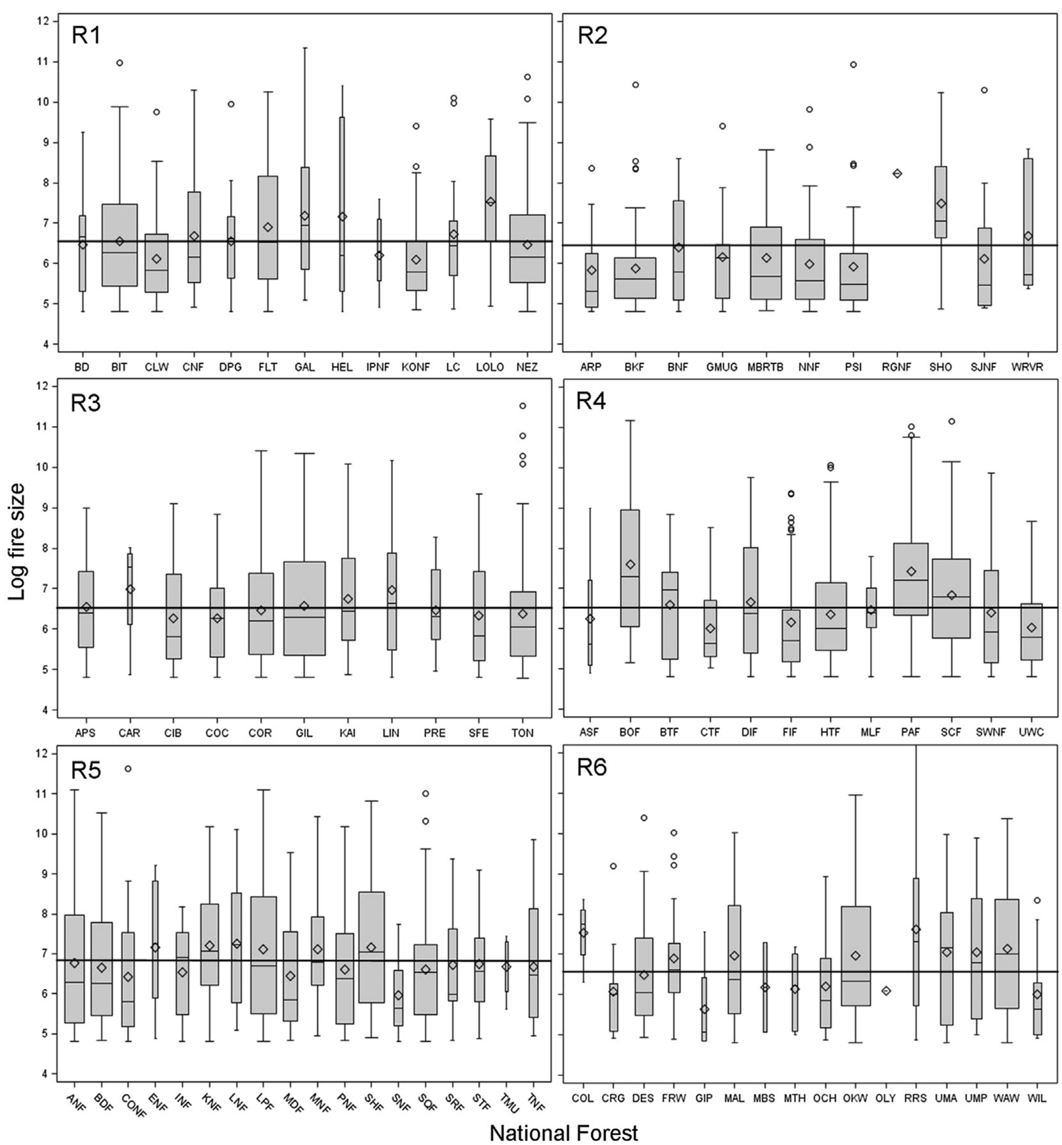

Fig. 3. Variable width box plots of log transformed fire size by national forest for the 82 national forests in the western US grouped by US Forest Service region. Width of the box indicates the relative number of fires. Diamonds indicate Forest means; thick black horizontal line indicates regional average. Data are from Short (2013) for the period 1992–2009. Average fire size excludes fires <121 ha.

some regional trends were apparent. Several Forests from Region 5 had the highest ignition densities (Angeles, Cleveland, San Bernardino) and also the highest rates of burning, which approached or exceeded 2% per year. The diversity in both burn and ignition rates among the Forests was striking, and illustrated that a wide range of ignition densities can achieve annual rates of burning from near 0 to almost 3%. Overall, the data show that ignition rate has not been a robust predictor of exposure to wildfires in terms of either percent or total area burned. Most ignitions (>80%) on the 82 Forests are caused by lightning although in some regions (e.g., Pacific Southwest) anthropogenic ignitions are a substantial cause of fires (49%) (Sup-Table 3).

3.2. Comparison of pre-settlement and simulated burn probabilities

Comparison of pre-settlement area burned based on mean fire return interval (MFRI) from LANDFIRE and simulated area burned showed that, with the exception of the Cleveland, simulated area burned was substantially less than the pre-settlement levels (Fig. 4C). The ratio of the mid-point pre-settlement MFRI burn probabilities (BP) and modeled FSIM BPs with fine scale (270 m pixel) outputs allows for the comparison and illustration of departure across the Forests (Fig. 5). The data showed a shift toward lower rates of area burned than estimated for historical conditions, especially in R2 (Fig. 5). However, in areas in southern California, central Arizona, and central Idaho the simulated burn probabilities are greater at present than pre-settlement.

3.3. Comparison of recent and simulated wildfire occurrence

Comparison of the modeled wildfire outputs with the results from the recent data showed a good correspondence (Fig. 4D). More detailed analyses and comparisons are provided elsewhere (Finney et al., 2011). The largest bias was observed for the Forest that had the lowest value of area burned, the Siuslaw. There were very few exceptions to the general trend, although the Rogue River-Siskiyou burned over twice as much area historically than simulated. This was primarily caused by the 2002 Biscuit Fire that burned over 200,000 ha − 16 times the average annual area burned recently.

3.4. Probability of mega-fires

The relationship between fire size and annual probability (Fig. 6) was nonlinear for most Forests, although the shape of the relationship varied considerably among Forests within regions. In general, for all Regions except Region 2, there was at least one Forest that had about a 0.05 annual probability of a fire that exceeded 40,000 ha. Seventeen of the Forests had a 0.10 annual

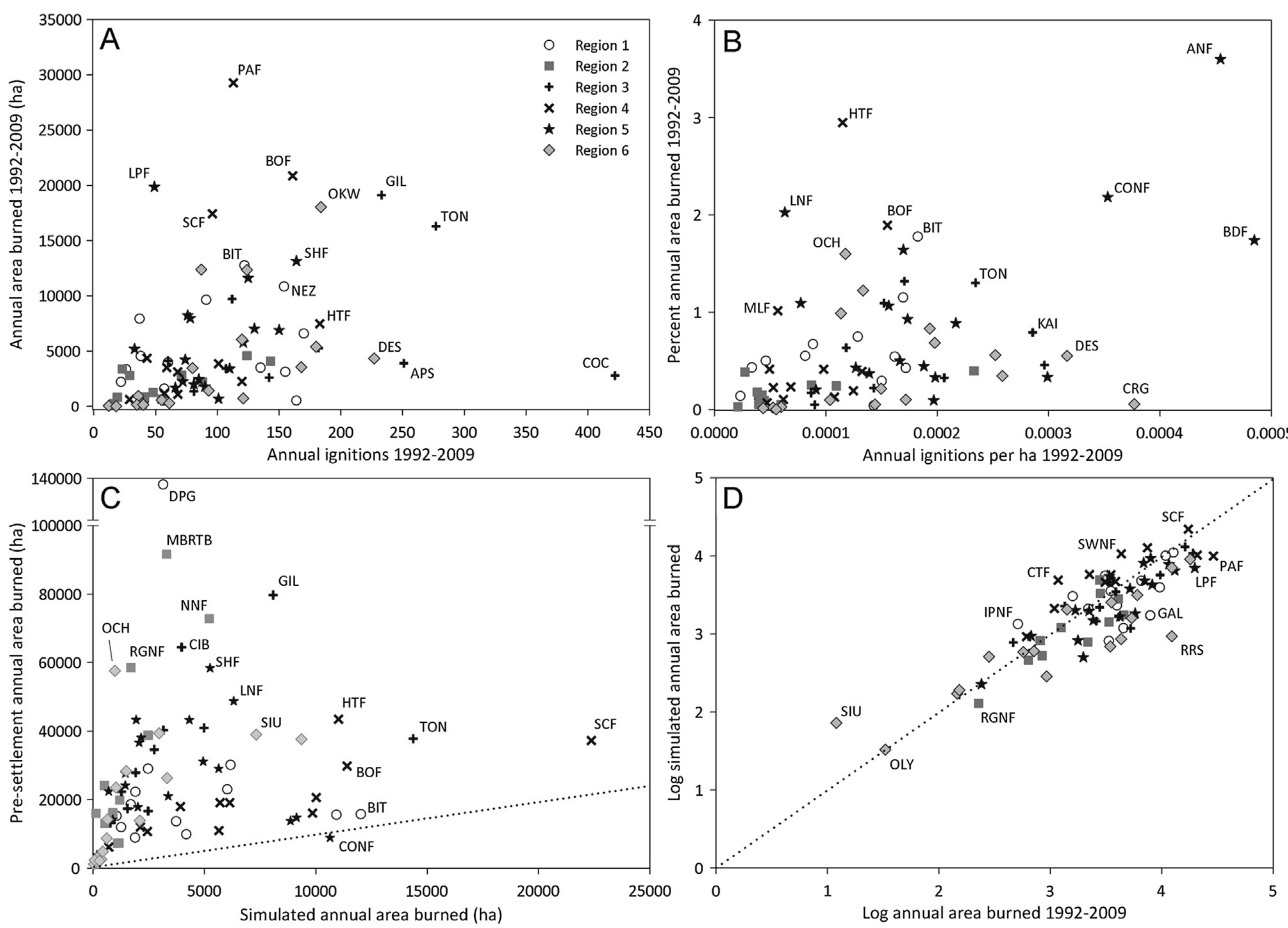

Fig. 4. Comparison of pre-settlement, recent, and simulated fire statistics by national forest (NF). (A) Recent annual area burned versus recent ignitions. Data include area burned off and within NFs from ignitions within NFs. (B) Percent area burned versus annual ignitions per hectare by Forest and region. Area burned off national forests from fires ignited on Forests was removed using land ownership data in the database. Note that area burned by fires that burn onto NF but were ignited outside NF boundaries was not counted. (C) Simulated annual area burned versus pre-European settlement expected annual area burned based on LANDFIRE (2013a) mean fire return interval (MFRI). Note break in y-axis. (D) Log transformed simulated annual area burned versus log transformed recent annual area burned. Simulated data in (C) and (D) include all area burned by fires (NF and non-NF) ignited within NFs. The dotted line in panels C and D represent the 1:1 ratio between the axes.

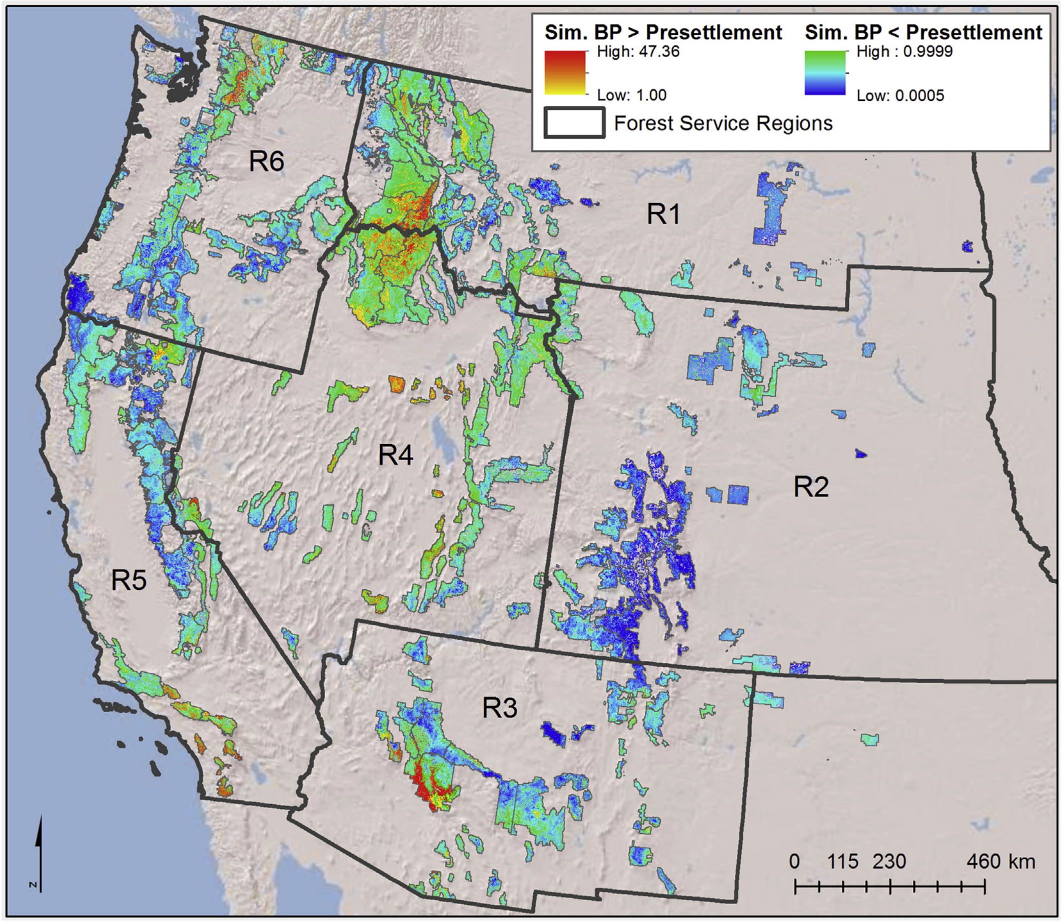

Fig. 5. Map of the ratio of simulated burn probabilities to derived pre-European settlement burn probabilities based on LANDFIRE (2013b) mean fire return interval (MFRI) for the 82 western national forests.

probability of a fire exceeding 8000 ha. Regions 4 and 5 had the highest probabilities of an extremely large fire (>100,000 ha) associated with one Forest within each region (Cleveland and Salmon-Challis). Note that the fire size data used to create Fig. 6 included area burned both on and off national forests.

3.5. Exposure at the subwatershed scale

Scatterplots for HUC6 watersheds within each Forest showed that mean BP and CFL were generally correlated, but that many Forests had a distinct profile in terms of the relative magnitude of the metrics. The plots clearly show numerous HUC6 watersheds with relatively high values of both BP and CFL compared to the overall population. Moreover, the plots showed different patterns among the regions in terms of the relationship between BP and CFL. The plots for Region 4 exhibited the largest amount of variation for both exposure components, reflecting diversity in the fire regimes within the region. Data for Regions 2 and 3 showed the strongest relationship between BP and CFL, meaning that sub-watersheds with the highest burn probability were also expected to burn at the highest intensity.

3.6. Fire transmission off national forests

The recent transmission of fires ignited on Forest lands to non-Forest lands (Fig. 8) showed wide variation among Forests. Large variation existed within a region, but in general the highest proportion of area burned off Forest land from fires that started on Forest land was seen in Regions 1, 4 and 5. For example Dakota Prairie grassland had very little total area burned, but was one of the largest contributors to fire transmission off the Forest. Several Forests in Region 4 had high area burned, but very little fire transmission to adjacent lands, while two Forests in the same region showed the opposite trend (Caribou-Targhee and Uinta-Wasatch-Cache), low area burned and the two highest percentage transmission values. We did not find that transmission was strongly related to either size or shape of individual Forests based on a coarse comparison of Forest boundaries with the transmission results.

3.7. Fire transmission to WUI populations

Simulated wildfires ignited on national forests burned through 4625 ha of WUI on an annual basis, which amounted to 0.077 percent of the total WUI area. Despite the small average value, large variation among Forests indicated that transmission of fire from national forests to adjacent WUI (Figs. 9A,B, 10) is of potential concern in some areas. The percent area burned for particular WUIs ranged from a minimum of 0% to a maximum of 3.9%, the latter found on a 330 ha WUI polygon adjacent to the San Bernardino. Sixty-three percent of the WUI areas (13,671 WUIs) had a 0% simulated area burned. The simulated annual population exposure for particular WUIs ranged from a minimum of 0 to a maximum of 65.4 people, the latter being a particular 526 ha WUI also adjacent to the Angeles. The relatively small numbers for the population exposure are to be expected given the estimates for the WUI area burned. In terms of Forest and regional patterns, several Forests,

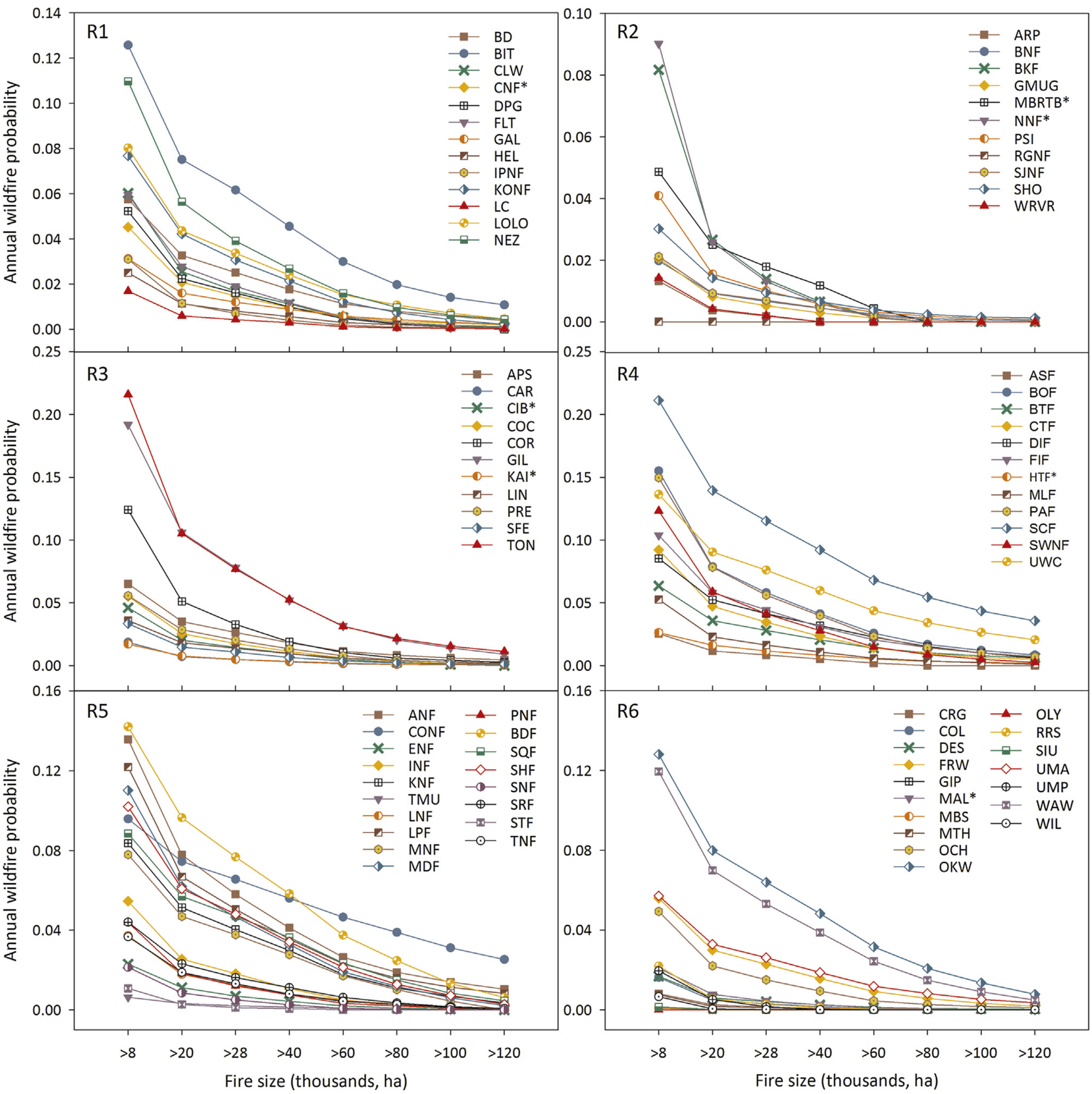

Fig. 6. Simulated annual probability of a wildfire of a given fire size assuming ca. 2008 landscape conditions and contemporary weather patterns by Forest and region in the western US. Data were calculated from the FSIM fire list outputs from Finney et al. (2011) and include area burned off national forests in the simulation. Asterisks indicate Forests that spanned multiple Fire Planning Units. See Section 2.8 for details. Note differing scales on the *y*-axes.

especially in the Pacific Southwest Region (R5) had the highest simulated population exposure from Forest Service wildfires (Fig. 9A). Several Forests in Region 1 (e.g., Bitterroot) showed relatively large areas of WUI expected to burn, but lower population densities on these Forests contributed to lower population exposure. Box plots of population exposure (Fig. 10) show both variation among and within the Forests, and the existence of outlier WUIs on specific Forests with unusually high population exposure.

3.8. Fuel treatment expenditures in relation to wildfire occurrence and budget allocation

The relationship between recent area burned versus fuel treatment budgets shows a broad positive relationship, although removing Pacific Coast Forests weakens the trend (Fig. 9C). A relationship between the fuel treatment budget and recent area burned within regions is also apparent, except for the Pacific Northwest Region, largely due to the coastal forests. Forests with high annual area burned, yet relatively low fuel treatment budgets included the Payette, Umpqua, Bitterroot and a few other Forests (Fig. 9C). The Intermountain Region (R4) had the largest number of Forests with high simulated area burned, but generally low fuel treatment budgets, while Regions 2 and 5 tended to have high fuel treatment budgets, especially San Bernardino (data not shown). Annual fuel treatment budget was weakly related to simulated annual area of WUI burned by NFS-ignited wildfires after excluding the coastal and west Cascade Mountain Forests in the Pacific Northwest Region (Fig. 9D).

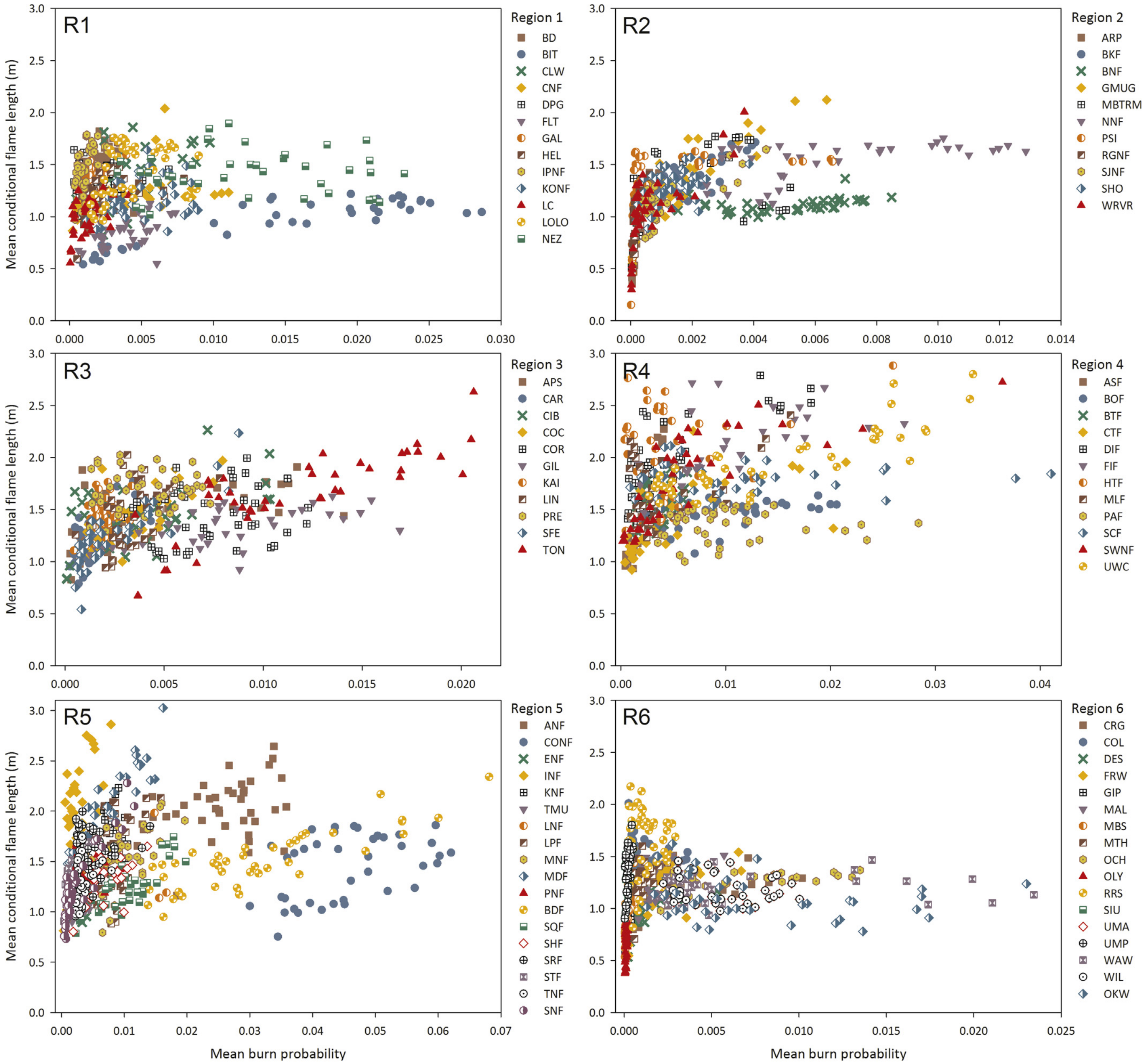

Fig. 7. Scatter plot of average conditional flame length versus burn probability for a random sample of 40 12-digit subwatershed HUCs by Forest and region in the western US. Outputs are derived from the flame length probability files in FSIM (Finney et al., 2011). Burned area estimated for fires that ignited both within and outside national forests. Note: Late Tahoe Basin (TMU) contains only four subwatersheds and Columbia River Gorge (CRG) contains only 17 subwatersheds.

3.9. *Forest ranking based on simulated exposure*

The ranking of the Forests based on the six wildfire simulation metrics showed clear differences in both the individual and total values (Fig. 11, Sup-Table 4). Forests that accounted for most of the exposure were primarily from the Pacific Southwest Region (R5). Less than 10% of the Forests accounted for 42% of the total exposure. The percentage change in the rankings from the top (1st) to the bottom (82nd) rank amounted to a more than a 100-fold difference in the metrics. Most of the variation in the rankings was from simulated population exposure, although the other metrics varied considerably as well.

4. Discussion

The goal of this study was to broadly characterize wildfire exposure among and within national forests in the western US, and compare these data with fuel treatment budget allocations. The study provides the first comprehensive, national forest-scale examination of wildfire exposure, and the results can be used as a foundation for risk-based management of fuel on the extensive network of fire prone national forests in the western US. Prior analyses of the FPA simulation outputs (Ager et al., 2012a; Finney et al., 2011; Thompson et al., 2011) and the fire occurrence database used for calibration (Short, 2013) also contribute to the broad

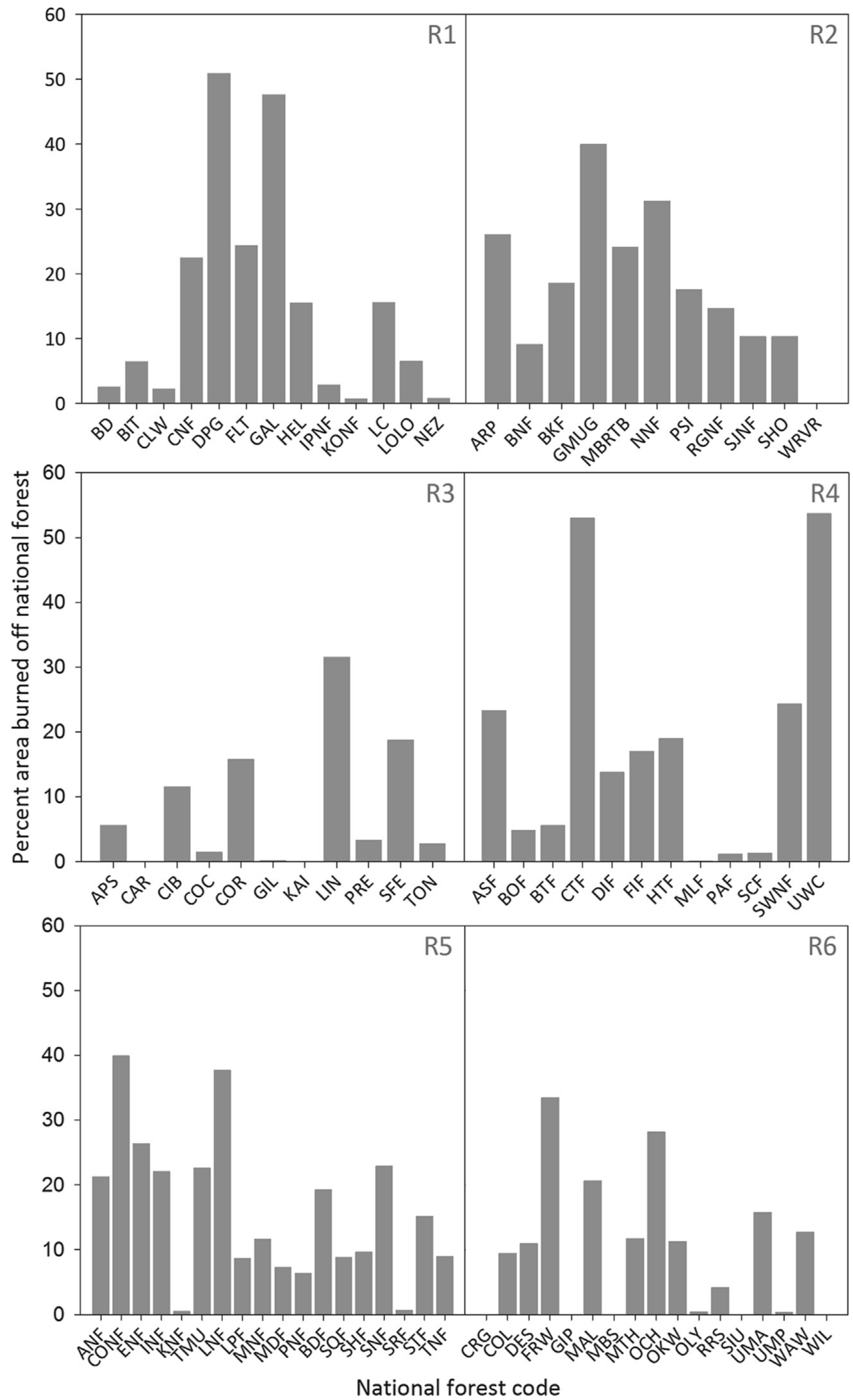

Fig. 8. Percent of non-Forest Service land burned by recent fires that ignited within national forests. Data are from FIRESTAT (2011) and include ignitions from 1990 to 2011 for fires >405 ha.

problem of mapping risk and exposure, although the current study presents several new approaches for creating metrics that describe different dimensions of wildfire exposure. Moreover, our stratification of the results by national forests allowed for detailed comparisons among predicted exposure and fuel treatment investments.

The simulation data in particular provided fine-scale maps of exposure components and wildfire transmission that have previously been unavailable to fuel management planners tasked with the problem of allocating limited fuel treatment budgets to address growing wildfire losses. The maps and data generated from the simulation modeling are consistent with historical fire frequency and current knowledge about fire ecology within the study area (Agee, 1993; Finney et al., 2011). The analyses led to the ranking of the Forests with respect to a selected set of metrics, and a clear differentiation in predicted wildfire activity as informed by simulation modeling. The information and methods can be used at multiple administrative scales within the Forest Service for budget allocations, and for more detailed assessment and mitigation planning at the local scale.

While analytical approaches to wildfire risk assessment continue to evolve (Miller and Ager, 2012), it is important to

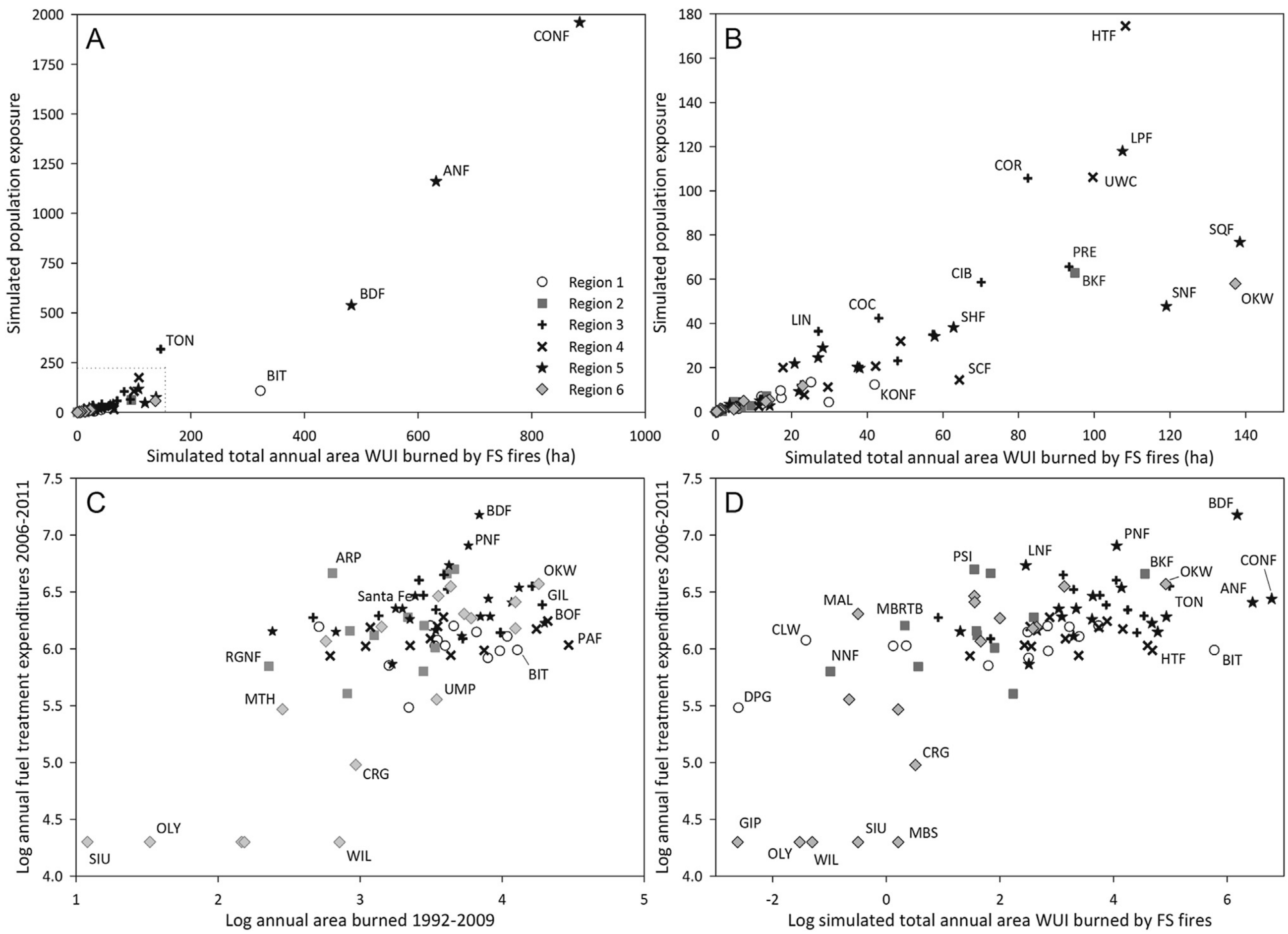

Fig. 9. (A) Average simulated annual area of Wildland Urban Interface (WUI) burned by fires ignited on national forests (NF) derived from FSIM fire perimeter outputs (Finney et al., 2011) versus average simulated population exposure. Simulated population exposure was calculated from population density for WUI multiplied by the proportion of WUI burned by fires ignited on NF. Population data are from LandScan USA (2009). Individual WUIs were assigned to the closest NF. Note break in *y*-axis. Dotted line box indicates graph area displayed in panel B. (B) Average simulated annual area of WUI burned versus average simulated population exposure, graphed to exclude outliers visible in panel A. (C) Average annual fuel treatment expenditures versus recent area burned. Recent data are from Short (2013) and include ignitions from 1992 to 2009. Data include all area burned by fires that ignited within NF. (D) Average annual fuel treatment expenditures versus average simulated annual area of WUI burned by fires ignited on NF. See Section 2.4 for details on fuel treatment expenditure data.

recognize the importance of fire regime in terms of quantifying risk and exposure, and designing mitigation strategies. The bulk of the research and application concerning wildfire risk concerns fire regimes characterized by relatively small (e.g., <5 ha) and frequent anthropogenic-caused fires (FAO, 2007). However, western US Forests are characterized by large fires (e.g., 10,000–100,000 ha) that burn for days or weeks and spread over long distances (e.g., 10–30 km). Thus the relative importance of fire spread versus ignition location is substantially different, and thus potential impacts of large fires are poorly represented by models that are based on localized risk components (e.g., ignition probability, fire occurrence data). Thus fire spread simulation modeling plays a pivotal role in large fire risk assessments since there is insufficient fire history data to generate maps of risk at a scale that is meaningful to fuel management planners.

The data indicate reasonably good correspondence between recent and simulated wildfire occurrence as measured by area burned, and that hazardous fuel reduction investments are coarsely related to recent area burned and simulated WUI area burned. Deviations from the overall trend are apparent, due to many factors that are specific to individual national forests including past mega-wildfire events, and special budgetary considerations for particular Forests.

We posed five interrelated questions at the outset of the study, the first being the relative magnitude of variation in the recent and simulated wildfire exposure among the 82 western national forests. This analysis was motivated by the fact that variation among Forests is the basis for prioritization of fuel management. Substantial variation in both recent and simulated fire occurrence was indicated by the empirical data and simulation modeling, and variation within regions exceeded that within Forests. We observed variation in average values of the different exposure variables, and per area differences as well. Although the observed variation among Forests is not surprising given the diversity of ecological settings, a comparative analysis has heretofore not been available. The results reinforce the potential value in a decision support system to prioritize fuel management investments among the national forests, and suggest careful attention be paid to the allocation process at the administrative scale at which the variation is the largest. In this case all of the data point to extensive variation among Forests within regions. It is interesting to note that the agency at this time does not have a consistent allocation process for fuels management at the sub-regional scale.

The second question pertained to the major trends among presettlement, recent, and simulated annual area burned. The mean fire return interval indicated that most Forests are burning at rates

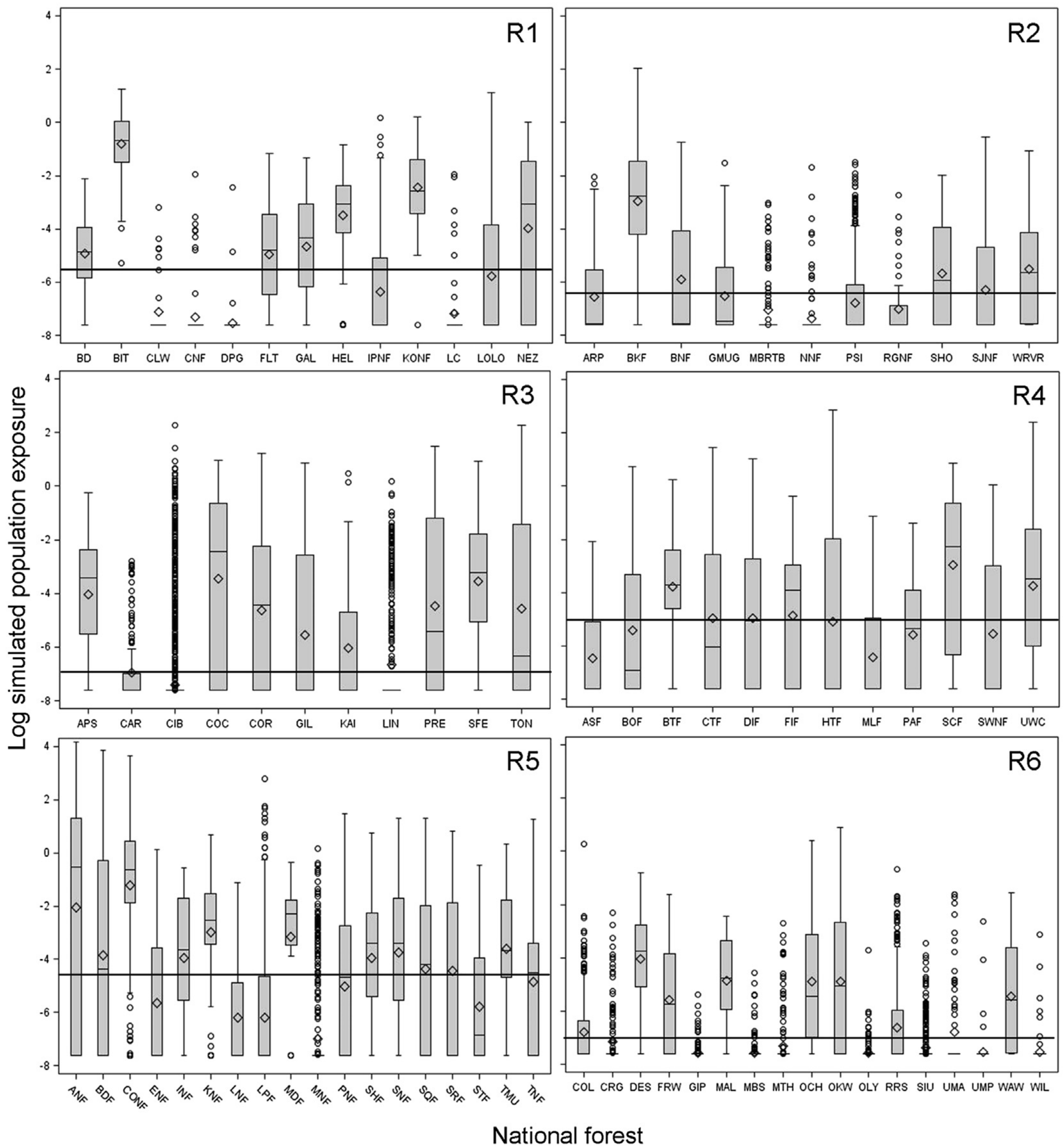

Fig. 10. Box plots of log transformed simulated population exposure on the 82 national forests (NF) in the western US. Simulated population exposure was calculated from population density for WUI multiplied by the proportion of WUI burned by fires ignited on NF. Population data are from LandScan USA (2009). Fire perimeters were derived from FSIM fire perimeter outputs (Finney et al., 2011). Individual WUIs were assigned to the closest NF.

less than pre-European settlement conditions when compared to the period 1991–2009 (with the exception of the Cleveland). The pre-settlement burning rate averaged over all national forests in the study was 1650% more than the current rate as measured from simulation outputs. These analyses suggest that returning to pre-settlement rates of burning with prescribed and managed fire will require a dramatic increase in the rate of burning (Sup-Table 4). For example, on the Rio Grande, to achieve the historical burn rate would require an increase in burning of over 11,000% above the current rate. In comparison, the Payette and Fishlake would require a doubling of the annual area burned to approach the pre-settlement annual rates (Sup-Table 4).

The map of the ratio of pre-settlement and simulated burn probability highlighted specific areas on the western Forests where the departure was the largest (Fig. 5). However, some areas such as southern California, central Arizona, central Idaho, central Cascades, and the northern Rockies had simulated burn probabilities greater than pre-settlement. This response could be for a variety of reasons. In southern California the increased rate of human ignitions compared to pre-settlement in conjunction with wildland urban interface (WUI) expansion has led to increased fire frequency (Lippitt et al., 2013; Syphard et al., 2007). In the Great Basin and central Arizona, invasive species such as cheatgrass have increased fine fuel loadings and contributed to increased rates of burning (Balch et al., 2013; Whisenant, 1990). In the forested areas of central Idaho, the Cascades of Washington, and the northern Rockies, a combination of fuel build-up due to twentieth-century suppression policies (Stephens and Ruth, 2005) and wilderness fire management policies have likely contributed to increased rates of burning (Heyerdahl et al., 2008; Morgan et al., 2014).

The comparison between recent fire occurrence and the simulated outputs was performed mostly to confirm that simulation outputs reflected recent fire history. The comparison indicated the latter was a good estimate of the former, thus enabling finer scale analyses than possible with limited fire history data. The FSIM simulations have been validated as part of FPA as well (Finney et al.,

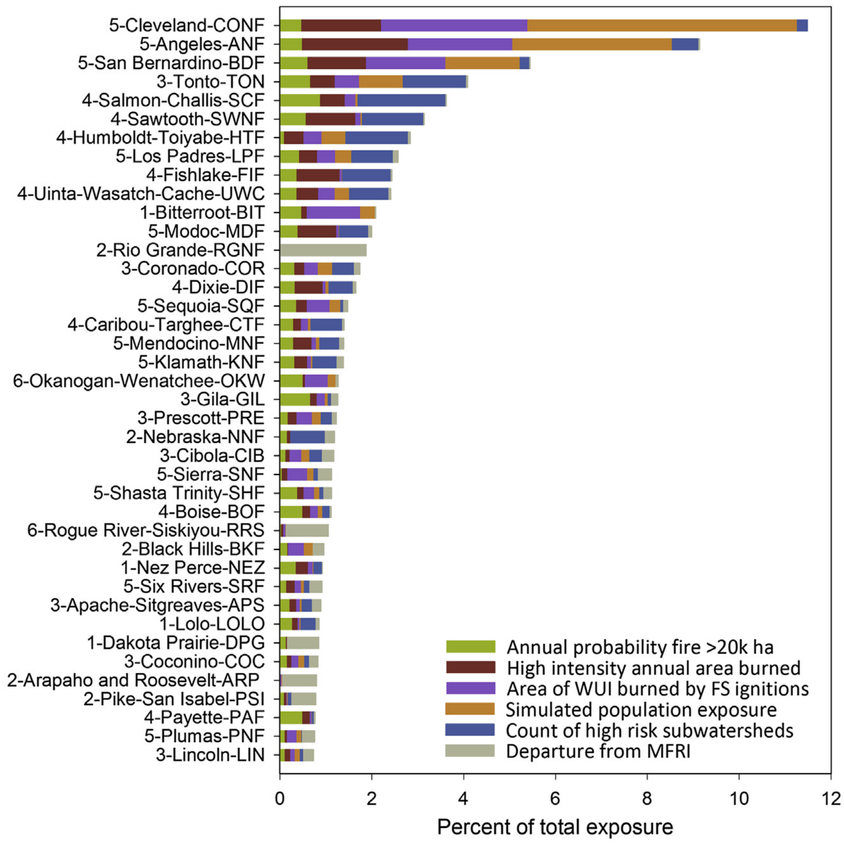

Fig. 11. Ranking results for the top 50% of western national forests (out of the 82 included in the study) in terms of six wildfire exposure variables from simulation outputs. The ranking was performed with simulation outputs since empirical data are insufficient to obtain robust estimates of key exposure parameters. The length of the bar represents the percentage contribution to the total westwide exposure for each metric. Numbers on the *y*-axis indicate region. See Section 2 for detailed descriptions of wildfire exposure variables included.

2011). The correspondence between the two suggests that in general, recent fires are not limited by fuels, since that condition would be manifested as an underestimate of burned area.

The third question concerned national forest fires impacting adjacent lands and WUIs. The recent fire occurrence data showed that a substantial amount of non-forest service land is burned by fires ignited on national forests, with the amount varying considerably among Forests. For instance, over 50% of the total area burned by fires ignited on three Forests (Uinta-Wasatch-Cache, Caribou-Targhee, and Dakota Prairie Grasslands) consisted of lands outside the Forest boundaries. While the shape and size of national forests most likely contributes to fire transmission, there were no obvious relationships among the Forests in the study. The coarse analysis of transmission from the historical fire record was augmented by the analysis of transmission using wildfire simulation outputs. That analysis identified Forests with the highest potential wildfire transmission to adjacent WUIs. Because our modified WUI layer was only 36% of the original layer for the western US (which excluded uninhabited WUIs), transmission rates may have been underestimated. However, our selection of WUIs highlighted those with the highest population density, burnable vegetation and a size appropriate for use with simulation data. The transmission of wildfire from federally managed lands poses a particularly difficult challenge for federal managers, especially when the federal lands are part of conservation or other protected reserves that prevent fuel management. Federal wildfires that spread to the urban interface cause the bulk of human and financial losses and are the primary driver behind the escalating federal fire suppression budget (Bailey, 2013). Roughly half of the national forest lands are in forest plan land designations that either prohibit or restrict mechanical treatments of fuels, leaving managed fire the sole method to reduce fuel loadings. The transmission of exposure and risk from national forests to adjacent lands is an important consideration for wildfire risk management in the context of realizing the new Federal Cohesive Strategy (USDA-USDI, 2014) goal for building fire adapted communities. An "all-lands" collaborative planning approach will be an important component of efforts to reduce risk transmission from federal to private landowners.

The fourth question concerned the forecasting of probabilities of mega-fires of specific sizes on each Forest. The results suggested that under weather conditions corresponding to the recent fire record, all regions except Region 2 had at least one Forest with about a 0.05 annual probability of a fire that exceeded 40,000 ha. Each Region had one to three Forests with considerably higher probabilities of fires in the range of 20,000–60,000 ha. The probability of a fire that exceeded 100,000 ha was 0–0.02, except for two Forests where the probability was between 0.04 and 0.05. Large fire probabilities were, in general highest for the Forests in Regions 4 and 5.

Finally, we asked how recent fuel management investments align with recent area burned. We found that, in general, there is a good correspondence between past investments and wildfire activity, suggesting that the fuel management priorities target investments to fire prone forests. However, we observed many exceptions to this general trend, in part due to the fact that fuel treatment budgets often include funding earmarked for other purposes and these are difficult to identify with the data made available for the study. Another reason for exceptions to the general trend is that a number of Forests, particularly in Region 3, mange wildfires for resource benefit, i.e., fuel treatments, and these Forests would appear to be underfunded based on wildfire area burned.

This study focused on analyzing exposure components and, with the exception of the WUI analysis, we did not examine values at risk, or attempt to quantify expected loss (Finney, 2005). Despite the lack of formal risk calculations to estimate loss, this study paves the way to advance the integration of risk assessment within the federal fire management policy, an improvement that has been suggested by oversight agencies (GAO, 2004, 2009). Previous papers have estimated wildfire risk for individual (Ager et al., 2007) and multiple values (Thompson et al., 2011), and there is broad interest in applying risk concepts for US federal fuels budget allocation and project planning. However, at the scale of this study, estimating risk requires valuing and quantifying fire effects for a diverse set of ecosystem services that are difficult to quantify (Venn and Calkin, 2011). We argue that exposure analyses are not only sufficient to inform risk management strategies, but also offer some advantages (Ager et al., 2012a) including a simplicity that facilitates communicating wildfire risk to managers. Fire effects relationships required for risk calculations are difficult to develop for many ecosystem services, such as visual quality, ecological integrity, and biodiversity, adding to the overall uncertainty of a formal risk assessment for highly stochastic wildfire events.

We recognize the many sources of uncertainty and error associated with modeled outputs (Ager et al., 2011). These include the LANDFIRE fuels data, and the assumed weather conditions for each of the simulated fires. However, comparisons between simulation outputs and historical wildfire data (Fig. 4) show that, at broad geographic scales (i.e., national forest), the modeling approach can replicate historical wildfire exposure reasonably well. The weather data are of particular concern since there is only one station used for each of the 17 FPUs that were used to spatially stratify the modeling for the 82 forests. However, the simulations can be refined as part of future, finer scale exposure assessments to inform local planning efforts (Ager et al., 2012b). For instance, wind data in particular can be processed through terrain models to provide detailed wind vectors to account for localized winds (Butler et al., 2006).

The ranking of the Forests with respect to the exposure metrics suggested large differences in the inherent exposure to wildfire. Although some of the differences are size-related, the variation is still significant from a budget allocation and total exposure standpoint. Moreover the two Forests with the highest exposure are about a third the average size of the national forests (c.f., Fig. 11, Sup-Table 1). The rankings were also fairly consistent among the Forests – those that were ranked relatively high in one category were ranked high in the others as well. Each of the metrics represented some different aspect of the wildfire problem, i.e., the likelihood of a future large mega-fire, departure from presettlement conditions, transmission to the WUI, and simulated burn probability and fire intensity as represented by flame length. We recognize that these metrics, averaged over large national forests (e.g., 500,000 ha) are only broad indicators, and finer scale analyses and mapping of variation within Forests (e.g., Fig. 7) are logical next steps to refine this work.

A remaining challenge for the wildfire risk science community concerns the integration of risk and exposure assessments into prioritizing programs within land management agencies such as the Forest Service. These agencies typically have a hierarchy of administrative units (e.g., regions, national forests, and districts), and thus prioritization models must span multiple scales to downscale and implement the results of risk assessments. For

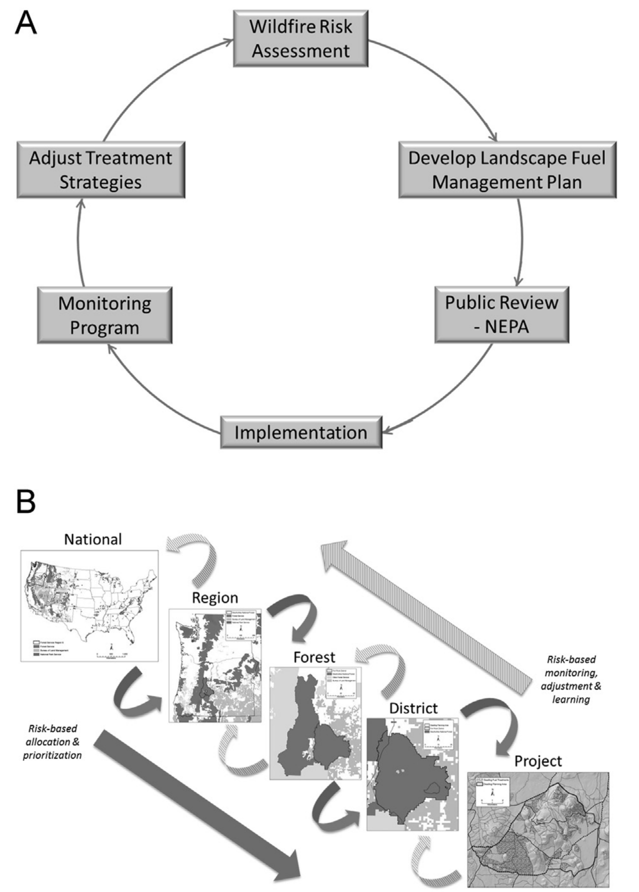

Fig. 12. (A) A risk assessment protocol for prioritizing fuel management investments. Regional risk assessments, which are derived from national risk assessments, are provided to Forests and used to develop budget proposals that explicitly address risk as identified in the assessment. Proposed Forest budgets are then leveled at the region, resulting in regional-scale reporting of risk factors and maps showing where and how wildfire risk is being mitigated. The leveling process is iterative until Forest fuel management proposals address the risk assessment products commensurate with the budget request. The protocol is repeated as significant changes in budget and wildfire risk change over time. (B) The concept of adaptive risk management implements a risk assessment protocol at multiple administrative scales, with downscaling of risk-based information for allocation and prioritization, and upscaling of monitoring, adjustment and learning.

instance, in the Forest Service, multiple models or assessment techniques exist, beginning with the national allocation to the 10 regions via the Hazardous Fuels Prioritization and Allocation System. Subsequent allocations to Forests within regions and districts within Forests are based on ad hoc methods that incorporate finer scale spatial data, but lack consistency and transparency, and potentially dilute national priorities. To facilitate a consistent use of risk-based approaches for allocating fuel treatment budgets, we suggest that risk and exposure assessments need to be incorporated into part of a multi-scale framework that includes defined protocols to downscale and implement the outputs, and provide important monitoring information to national programs (Fig. 12). Such a protocol would help managers understand how different landscape fuel treatment strategies (Ager et al., 2010; Collins et al., 2010; Finney et al., 2007; Graham et al., 2010; Reinhardt et al., 2008; Schmidt et al., 2008), affect specific risk factors (intensity, likelihood, exposure, and susceptibility) over time. By linking the various scales with a consistent protocol, the framework potentially provides a means for monitoring risk, and adapting national investment strategies based on trajectories at local scales. The concept of our proposed multi-scale approach for risk management has application to other fire management programs as well, including the Cohesive Strategy (USDA-USDI, 2014), Fire Program Analysis (FPA, 2010), fuel treatment effectiveness monitoring (Bostwick et al., 2011; Hudak et al., 2011; Keller, 2011), and real time wildfire decision support (Noonan-Wright et al., 2011).

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Appendix A. Supplementary material

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jenvman.2014.05.035.

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