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Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk

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ABSTRACT

We examined the financial efficiency and effectiveness of landscape versus community protection fuel treatments to reduce structure exposure and loss to wildfire on a large fire-prone area of central Idaho (USA). The study area contained 63,707 structures distributed in 20 rural communities and resorts, encompassing 13,804 km^2. We used simulation modeling to estimate expected structure loss based on burn probability and characteristics of the home ignition zone. We then designed three fuel management strategies that targeted treatments to: 1) the surrounding areas predicted to be the source of exposure to communities from large fires, 2) the home ignition zone, and 3) a combination of the landscape and home ignition zone. We evaluated each treatment scenario in terms of exposure and expected structure loss compared to a no-treatment scenario. The potential revenue from wood products was estimated for each scenario to assess the cost-efficiency. We found that the combined landscape and home ignition zone treatment scenario which treated 5.7% of the study area resulted in the highest overall reduction in predicted exposure (47.5%, 100 structures yr^{-1}) and predicted loss (69.1%, 57 structures yr^{-1}). Home ignition zone treatments provided the best predicted economic and per area treated performance where exposure and loss were reduced by one structure by treating 89 and 111 ha per year, respectively, with an annual cost of $33,645 and $73,672. Revenue from thinning was the highest for landscape fuel treatments and covered 16% of the required investment. This work highlighted economic and risk tradeoffs associated with alternative fuel treatment strategies to protect developed areas from large wildland fires.

1. Introduction

Fire impacts to developed areas are growing globally and underscore the need for additional research to identify long-term solutions (Braziunas et al., 2020). For instance, on average, wildfires in the western USA exposed 9,990 structures and destroyed 3,562 annually over the last twenty years (St Denis et al., 2020), but the past five years have shown sharply increasing loss rates, suggesting a new normal where large destructive fires can be expected every fire season (Ager et al., 2021a; Syphard and Keeley, 2019). Wildfire risk from large fires has many drivers including ignition patterns, fire spread, variation in building susceptibility, and suppression tactics within developed areas. Relatively few fires account for the bulk of structure losses, and many of these events have been intensively studied to understand the drivers of loss in relation to housing density and arrangement, fuels, and building construction (Alexandre et al., 2016b; Kramer et al., 2019). Once fires reach developed areas, structure loss is strongly dependent on hazardous fuels, housing arrangement, and road network density in the home ignition zone (HIZ) (Alcasena et al., 2017; Alexandre et al., 2016a; Calkin et al., 2014; Cohen, 2008; Syphard et al., 2017). While fire exclusion and inadequate forest and fuel management on forest lands surrounding communities can substantially increase wildfire exposure, rapid expansion of the developed areas (Radeloff et al., 2018), increasing human ignitions and local fuels in the HIZ are also contributing factors (Mietkiewicz et al., 2020b; Nagy et al., 2018).

US federal and state fire protection policies have been implemented in recent years to create a myriad of programs that focus on the community scale to reduce in situ risk and improve adaptation to wildfire (Mockrin et al., 2020). Meanwhile, federal agencies have expanded fuel treatment and restoration programs to increase the pace and scale of

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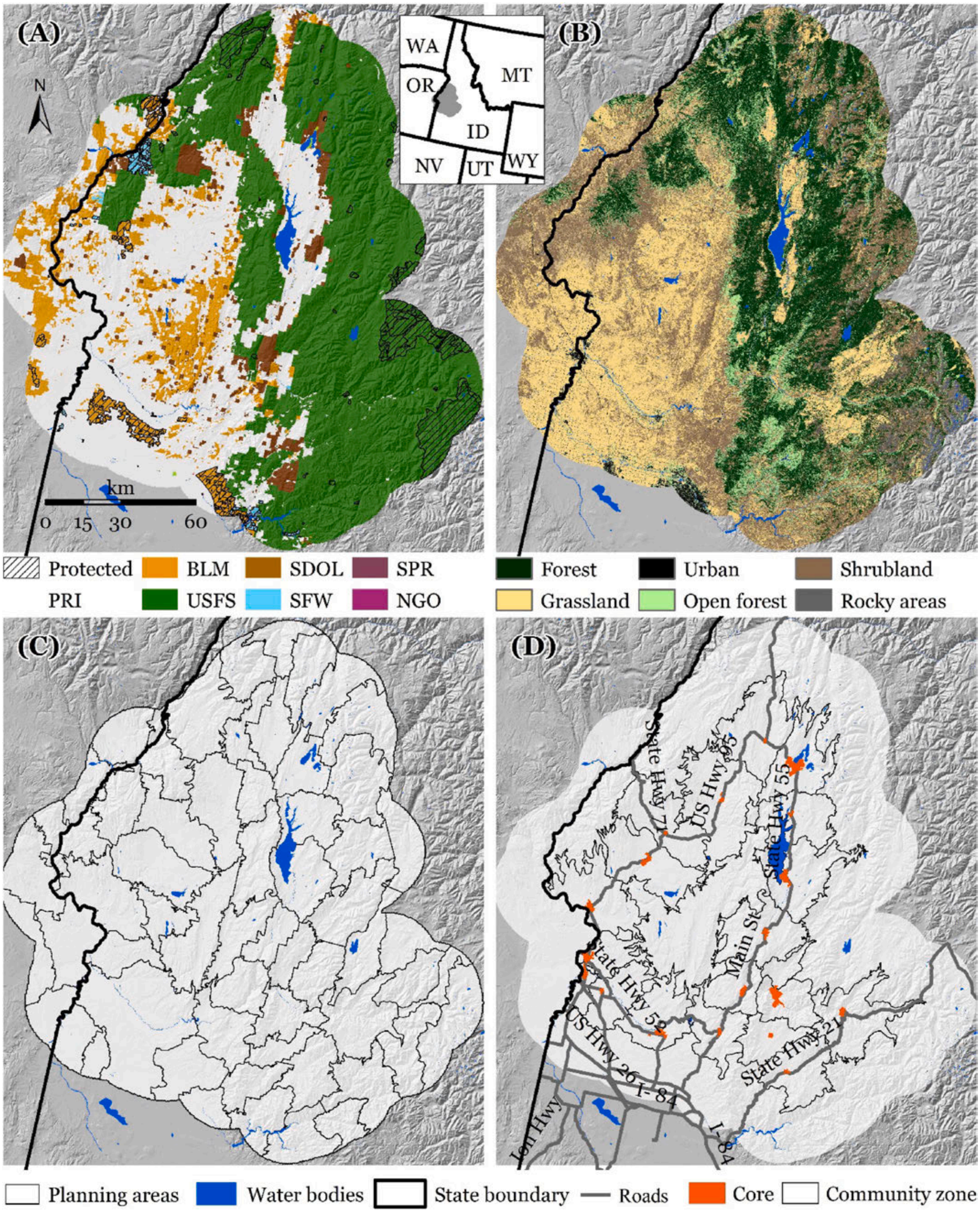

Fig. 1. Land tenure systems (A), broad vegetation classes (B), pre-defined planning areas (D), and communities (C) in the central Idaho, USA study area.

management with the focus of creating fire-resilient forests with safe and efficient response in the lands surrounding developed areas (USDA Forest Service, 2014). In an attempt to bring about a convergence of mitigation strategies across scales and ownerships, an "all-lands" shared stewardship program was created by the Forest Service to allocate funding to cross boundary management efforts among stakeholders, forest managers, Tribal Nations, public agencies, firefighters, and communities to design and implement coordinated, cross boundary investments in fuels reduction (Charnley et al., 2020; Nielsen et al., 2019; USDA Forest Service, 2018). All-lands efforts focused on wildland urban interface (WUI) protection can include a broad array of coordinated mitigation measures including forest landscape restoration to improve fire resiliency, and more focused treatment in the WUI aimed at reducing building susceptibility (Ager et al., 2015).

Although policies are increasingly promoting all-lands and multi-scale approaches to protect developed areas, the relative effectiveness of fuel treatments for community protection versus landscape restoration are widely discussed in terms of which one is more effective, and viewed as alternatives rather than considering them both as a multi-scale approach (Ager et al., 2021b). Landscape restoration and fuel treatments reduce the probability of fire spread to developed areas and structure exposure from direct flames or ember showers (Salis et al., 2018; Scott et al., 2016; Tubbesing et al., 2019). On the other hand, fuel reduction in the HIZ, typically a 30- to 60-m buffered area around a home (Cohen, 2008; National Fire Protection Association, 2018), can help prevent housing destruction by reducing fire intensity and creating a safe defensible space around structures (Kolden and Henson, 2019; Penman et al., 2019). A number of studies have concluded that treatment of fuels in the HIZ are more effective at reducing loss than distant treatments distributed across the landscape, including both empirical and simulation studies (Bradstock and Gill, 2001; Braziunas et al., 2020; Cary et al., 2009; Syphard et al., 2014). This is not surprising since fuel treatments adjacent to structures directly target the source of embers that are most likely to cause initial ignitions that trigger mass structure loss events (Calkin et al., 2014). However, it is important to recognize that empirical studies of structure loss do not generally include fire events where landscape fuel treatments prevented spread to developed areas in the first place, since there was no structure loss to sample (but see Gibbons et al. (2012)).

One important factor that has not been considered is the relative cost and financial benefits of landscape versus community protection treatments relative to their effectiveness. Reducing building susceptibility to wildfire can require expensive investments in construction materials and removal of non-commercial vegetation by unwilling landowners, whereas landscape fuel treatments when coupled with restoration (Stephens et al., 2021) can generate revenue that offsets treatment costs. Landscape fuel treatments can also be expensive when commercial forest management is not included as part of restoration treatments (Belavenutti et al., 2021), and federal funding to support non-commercial projects is severely limited relative to the levels of current risk. This tradeoff between economics of risk and treatment scale is a knowledge gap that could alter the practical implications of prior work, tipping the balance towards landscape approaches when revenue from restoration enables a substantial increase in treated area (Belavenutti et al., 2021).

To examine how commercial forest restoration activities potentially alter scale tradeoffs reported in prior studies we examined three scenarios where forest and fuel reduction treatments were either focused in the WUI, the surrounding landscape, or combined to treat both. The study area was a 1.4 million ha large fire-prone area of central Idaho, USA, where vast forested areas surround a large number of developments including resorts and rural communities. We measured the response in terms of treatment revenue, costs, and predicted structure exposure and losses. The results were used to compare alternative fuel treatment and restoration strategies in terms of their investment efficiency, and to examine how optimal treatment strategies might vary among the smaller planning area scale (e.g., 15,000 ha) at which fuel management and restoration treatments are implemented on US national forests.

2. Material and methods

2.1. Study area

The study area in central Idaho, encompasses 13,804 km^2 (Fig. 1). Private lands (PRI) represent 36% of the study area and public lands cover the remainder, including Forest Service (USFS) at 48%, Bureau of Land Management (BLM) at 11%, State Department of Land (SDOL) at 4%, and State Fish and Wildlife (SFW) at 1% (USGS, 2020). Other land tenures such as Non-Government Organization (NGO) and State Park and Recreation (SPR) lands have a limited presence ($<$1%). Protected lands with management restrictions for mechanical treatment implementation (e.g., wilderness) account for 7% of the study area, primarily located on BLM and USFS lands. The vegetation varies according to changing climatic conditions and topographic gradients. The southwestern portion is a vast plain dominated by dry grasslands and big sagebrush shrublands (LANDFIRE, 2020). In contrast, conifer forests dominate the mountainous eastern side except for the agricultural grasslands covering the valley bottoms. Perennial graminoid grasslands and deciduous shrublands sparsely cover the highest elevation peaks above the tree line. The mid- and lower-elevation temperate forests represent a historically frequent-fire adapted ecosystem, but old-growth selective harvests plus fire exclusion policies over the last century converted the landscape into a hazardous fuel continuum (Prichard et al., 2017). Notable contemporary wildfires include the 2007 Cascade Complex fire (70,511 ha), the 2012 Trinity Ridge fire (59,423 ha), the 2012 Idaho City Complex fire (59,248 ha), and the 2009 East Zone Complex fire (48,595 ha) (MTBS, 2020).

We used land ownership data (USGS, 2020) to delineate planning areas (n = 59), adding small polygons to the largest neighboring units until they reached a minimum size of 15,000 ha (Fig. 1C). The stratification into planning areas was done to replicate the scale at which federal and state restoration and fuel management projects are implemented, typically in a sequence determined by treatment priorities. The treatment units were then generated as a 20-ha hexnet nested to planning areas. We attributed the treatment units (n = 152,565) with planning area ID, ownership code, wildfire transmission prioritization metrics, thinning volume, treatment cost, structure data, the average slope of the terrain, and a protected area designation binary flag. We also divided the study area into community zones to aggregate the developed areas into blocks of similar extent (n = 20 of a ~50,000 ha average size) and summarized exposure and risk results (Fig. 1D). About 55,000 inhabitants populate the study area, and most communities are located close to main roadways, such as state highways 52, 55, and 71. These community zones were delineated using census blocks (US Census Bureau, 2018) as community cores plus the posted road speed to estimate the distance for 45-min drive time polygons (Ager et al., 2021a; Bunzel et al., 2021).

2.2. Wildfire spread simulation modeling

We simulated wildfire spread using the MTT algorithm (Finney, 2002) as implemented in the FConstMTT command-line program (Ager et al., 2019b; Alcasena et al., 2021; Salis et al., 2021). The MTT algorithm finds the shortest path by calculating the travel times from each node or cell corner to every other node on the landscape. It then predicts surface fire growth and ember emission in the different segments (Albini, 1979; Rothermel, 1972; Scott and Reinhardt, 2001). The required inputs include a landscape file (surface fuel, canopy metrics, and terrain grids), fire-weather scenario data (winds, fuel moisture content, and duration), and a fire ignition density grid to allocate the ignitions. The landscape grid was assembled at 60-m resolution using

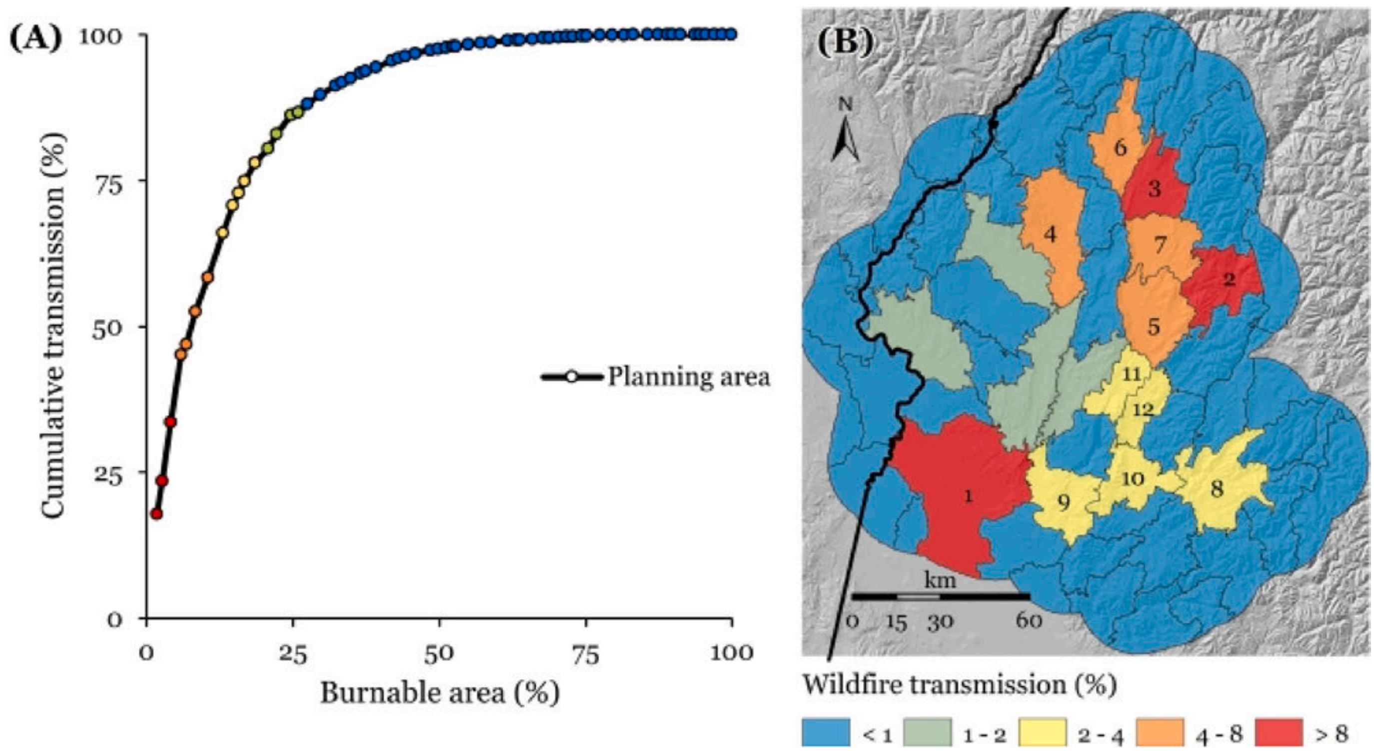

Fig. 2. Cumulative wildfire transmission to communities (% exposed str. yr^{-1}) and cumulative area bured by planning area (A) and the associated spatial composition (B). The high-transmission top planning areas ranked from 1 to 12 (out of a total of 59) covered less than 25% of the burnable area and accounted for more than 85% of wildfire transmission.

the 2016 LF.2.0.0 refresh data from LANDFIRE (Scott and Burgan, 2005). We delineated a 27,280-km^2 fire modeling domain landscape extending beyond the community zone areas with a 20-km buffer to allow for transmission of large wildfires ignited in the neighboring areas. We used automatic weather station hourly records to characterize the wildfire season extreme (97th percentile) fire-weather conditions with Fire Family Plus (Bradshaw and MacCormick, 2000). Specifically, wind scenarios were derived for the most frequent directions occurring during the wildfire season, and fuel moisture content was derived assuming the ERC-G reference conditions (Nelson, 2000). See fire spread modeling and calibration details in Appendix A.

We first simulated pre-treatment conditions, and then re-simulated fires for each management scenario after the fuel treatment implementation. Outputs included fire perimeter polygons, ember landing location point files, and conditional burn probability grids. The pixel-level annual burn probability was determined at 60-m resolution as:

$$aBP = \frac{n_{xy}}{Y} \tag{1}$$

where the aBP is the annual burn probability grid, n_{xy} is the number of times the xy-th pixel gets burned from surface fire or landing embers, and Y is the number of modeled years (n = 10,000) (Finney et al., 2011). By integrating landing ember locations in the aBP, we can better capture the intricate exposure patterns in the WUI areas where substantial exposure from showering embers is often present.

2.3. Wildfire transmission to communities

We conducted a transmission analysis to identify the source of wildfire exposure to communities (Alcasena et al., 2017). The transmission from escaped wildfires depends on a fire ignition occurring within the modeling domain and the potential for the fire to spread and expose structures in burned areas. In this study, we used transmission outcomes with the dual purpose of identifying planning areas that are the highest source of exposure and designing the treatment allocation within these high-transmission planning areas.

The planning areas for further analyses were selected based on predicted annual transmission to communities. This analysis allowed us to exclude remote portions of the study area where fires rarely pose a threat to communities and concentrate our treatment efforts on a reduced area. We calculated the annual wildfire transmission to communities from planning areas as:

$$TF_j = \sum_{i=1}^{n} S \Big/ Y \tag{2}$$

where the TF_j is the transmission (# exposed structures yr^{-1}) from all the fires ignited within the j-th planning area, S is the number of structures intersected by the i-th fire from a set of n total number of ignitions within the j-th planning area, and Y is the number of modeled years (n = 10,000) (Ager et al., 2014). We determined the total number of exposed structures (S) for each fire ignition intersecting the 132,892 modeled fire perimeters by using 63,707 structure centroids derived from building footprints (Microsoft, 2018). The planning areas were then ranked by transmission value to identify the high-priority planning areas accounting for the bulk of exposure sources (>85%) (Fig. 2A).

The treatment unit selection required a fine-resolution smoothed grid capturing the existing spatial gradient of wildfire transmission to communities to prioritize strategic stands within high-transmission planning areas (Fig. 2B) (Alcasena et al., 2018). We calculated a wildfire transmission index (TI) smoothed grid as:

$$TI = aID \times cTF_{90} \tag{3}$$

where TI is the transmission index (values between 0 and 100), aID is the annual ignition density, and cTF_{90} is the conditional wildfire transmission for the fire size threshold accounting for 90% of annual exposure. See wildfire transmission details and grids in Appendix B.

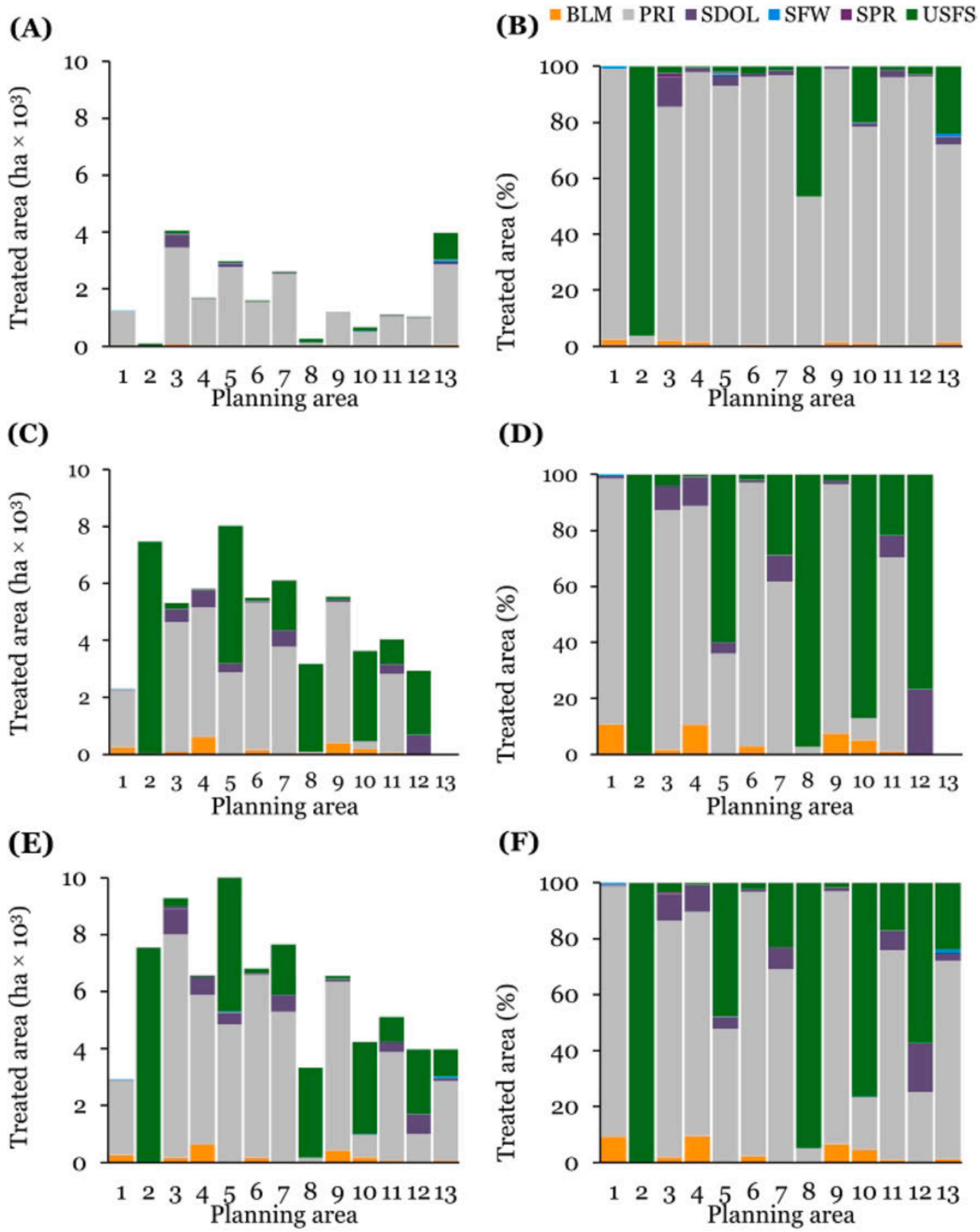

Fig. 3. Area treated and by percentage by land tenure in the different planning areas for the home ignition zone (HIZ, A and B), landscape (C and D), and combined (E and F) fuel treatment strategies. Landscape fuel treatments treated 20% of the area of hazardous fuels in high-transmission planning areas, whereas HIZ treatments reduced hazardous fuels within a 100 m buffer area around all structures. Note that planning area 13 represents lands within the study area outside of the pre-determined planning areas; only HIZ treatments were applied there (Fig. 2B).

2.4. Estimating expected structure loss

Expected structure loss was estimated as:

$$eLoss = aBP \times cLoss \tag{4}$$

where the *eLoss* is the expected % structure loss yr^{-1}, the *aBP* is the annual burn probability from surface fires and showering embers, and the *cLoss* is the predicted loss conditional on a fire encountering a structure. We predicted the latter as a percentage of structure loss using the logistic model:

$$cLoss\,(\%) = 0.21 - 0.95SD - 0.10RD - 0.78CI + 1.05HF \tag{5}$$

where the *SD* is the structure density (# structures m^{-2}), *RD* is the road density ($m\ m^{-2}$), *CI* is the contagion index, and *HF* is the percentage of highly flammable land (%) in the structure cluster(s) (see the model in Alexandre et al., 2016a). The model was constructed with empirical loss

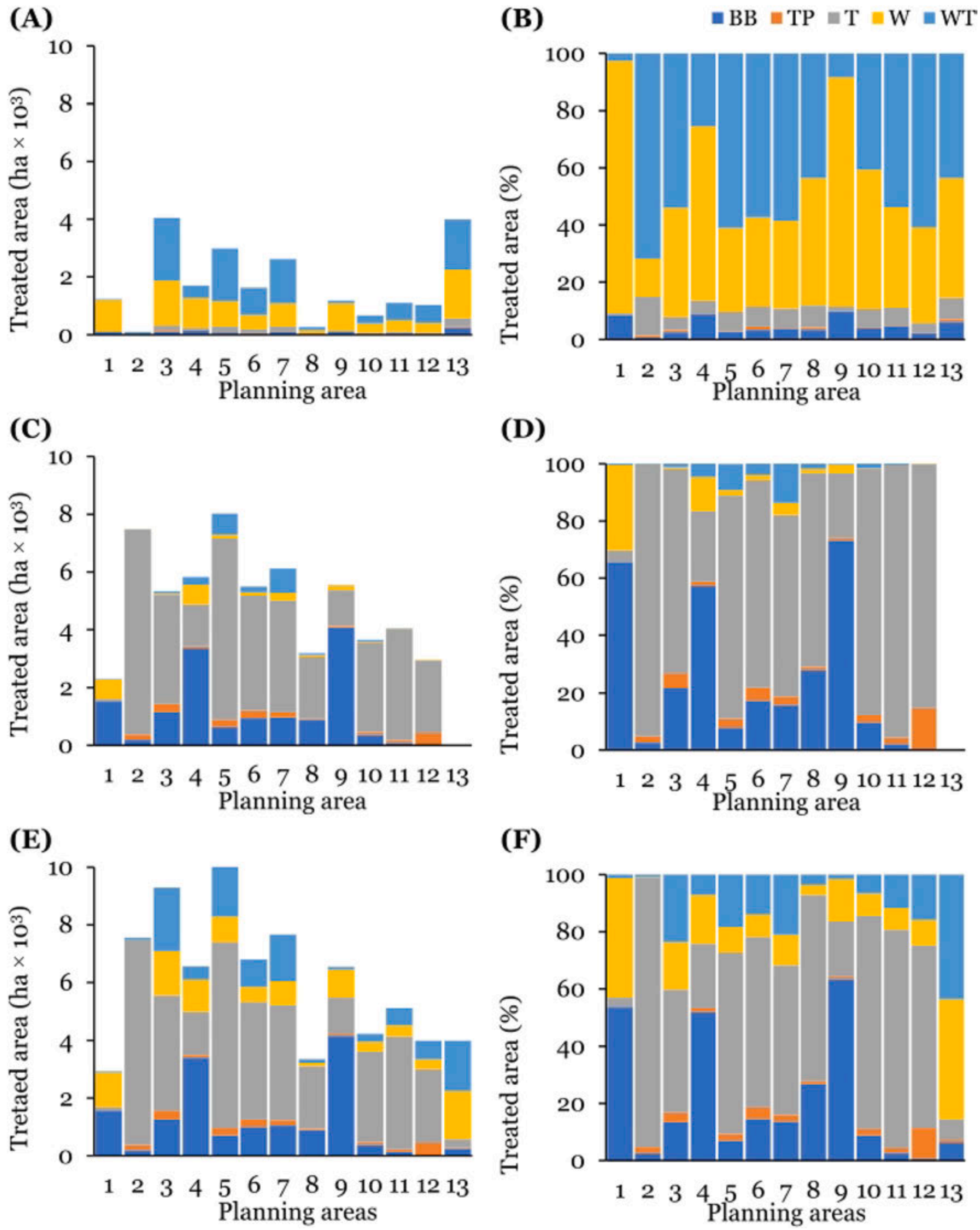

Fig. 4. Area treated and by percentage by treatment type in the different planning areas for the home ignition zone (HIZ, A and B), landscape (C and D), and combined (E and F) fuel treatment strategies. Note that planning area 13 represents lands within the study area outside of the predetermined planning areas; only HIZ treatments were applied there (Fig. 2B).

Table 1

Community-level modeled wildfire exposure and risk (# structures yr^{-1}) for current conditions and management scenarios, including landscape treatments, home ignition zone (HIZ) fuel reduction, and the combination of both. The combined scenario integrates landscape fuel treatments in high-transmission planning areas and the HIZ buffer treatments. Results for individual structures located outside of community zones (e.g., remote wilderness areas) have been summarized as other.

Community zones		Wildfire exposure to communities				Wildfire risk to communities			
Name	# str.	Current conditions (# exposed str. yr^{-1})	Landscape treat. (# exposed str. yr^{-1})	HIZ treat. (# exposed str. yr^{-1})	Combined treat. (# exposed str. yr^{-1})	Current conditions (# lost str. yr^{-1})	Landscape treat. (# lost str. yr^{-1})	HIZ treat. (# lost str. yr^{-1})	Combined treat. (# lost str. yr^{-1})
Banks	266	3.17	3.02	2.64	2.73	1.21	1.19	0.70	0.73
Cambridge	1,678	3.16	2.89	2.77	2.40	1.52	1.43	0.93	0.80
Cascade	3,663	18.08	13.50	6.76	5.73	13.61	10.15	3.56	2.87
Council	3,043	20.20	10.55	14.44	9.09	7.27	3.51	3.50	2.16
Crouch	1,762	5.21	4.43	1.47	1.49	2.90	2.48	0.59	0.61
Donnelly	3,611	9.65	7.02	5.45	4.47	5.86	4.11	2.35	1.93
Emmett	10,945	51.94	32.75	39.82	30.16	5.93	3.23	2.98	2.16
Fruitland	4,775	0.52	0.47	0.48	0.50	0.02	0.02	0.02	0.02
Garden Valley	788	5.72	5.31	3.80	3.59	2.42	2.28	1.17	1.08
Horseshoe Bend	1,993	11.16	9.71	8.40	7.96	2.67	2.13	1.24	1.16
Idaho City	942	2.95	2.89	1.80	1.80	1.40	1.40	0.63	0.64
Lowman	524	7.50	4.19	4.90	3.07	3.12	1.61	1.62	0.91
McCall	7,299	29.00	27.40	9.83	8.10	17.80	16.72	4.36	3.66
Midvale	1,299	1.55	1.39	1.31	1.20	0.31	0.24	0.19	0.17
New Meadows	1,869	14.10	11.01	8.41	7.68	7.49	6.20	2.94	2.74
New Plymouth	4,122	5.48	5.48	5.30	5.44	0.45	0.46	0.33	0.35
Payette	5,709	0.77	0.76	0.74	0.82	0.03	0.03	0.02	0.02
Placerville	577	1.23	1.33	0.71	0.51	0.79	0.84	0.34	0.25
Smith's Ferry	957	8.19	7.31	5.58	5.38	4.05	3.53	1.75	1.64
Weiser	5,933	3.62	3.73	3.30	3.58	0.15	0.15	0.10	0.11
Other	1,952	7.91	6.62	6.01	5.19	3.28	2.72	1.75	1.42
Total	63,707	211.11	161.78	133.89	110.87	82.28	64.43	31.06	25.41

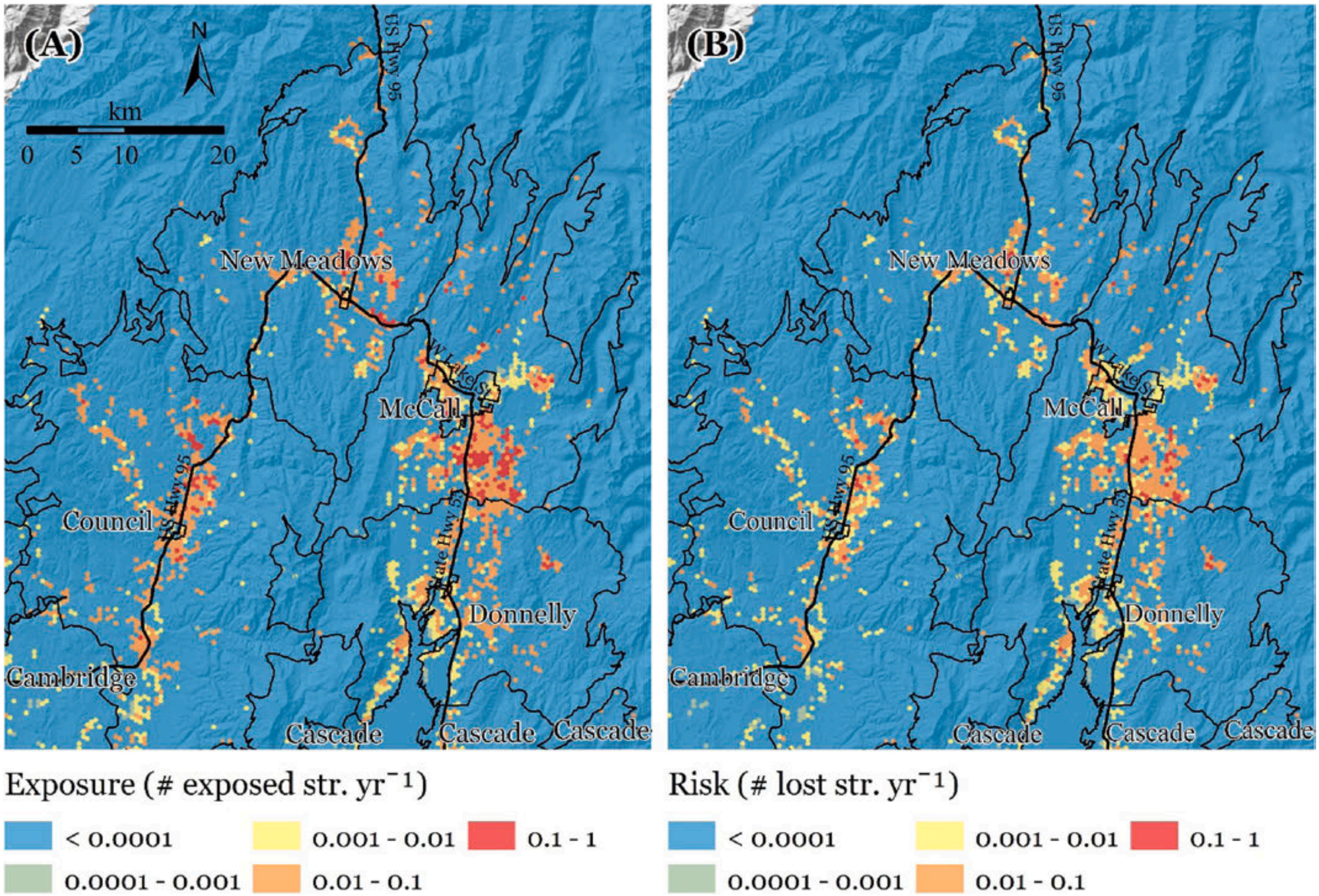

Fig. 5. Wildfire exposure (A) and risk (B) to structures for the northern portion of the study area. The values represent the sum per stand or treatment unit for the current conditions. The polygons are the community boundaries (Fig. 1D).

data from large fires between 2000 and 2010 (Alexandre et al., 2016a). We used individual structure footprints (n = 63,707) to delineate community clusters as a 100-m buffer around structure centroids (Microsoft, 2018). The *CI* index measures the aggregation degree of community clusters or patches; it represents a metric capturing structure-to-structure fire transmission in the WUI, and was calculated with FRAGSTATS (McGarigal et al., 2002). The *HF* describes the wildfire hazard to structures and is correlated with potential housing loss, determined from 2016 National Land Cover Database (Homer et al., 2020).

2.5. Simulated fuel treatments

Fuel treatment scenarios included: 1) landscape-scale strategic treatments; 2) home ignition zone (HIZ) fuel reductions, and 3) a combined strategy that included both of the former. A no treatment scenario was also simulated to use as a benchmark for the treatment scenarios. The HIZ scenario targeted treatments in a 100-m buffer area surrounding structures, and the landscape scenario prioritized treatments in the priority planning areas (n = 12) as determined from an assessment of wildfire transmission (>85% exposed str. yr^{-1}) (Fig. 2B). For the latter, we used the ForSys scenario planning model (Ager et al., 2021b) to optimally allocate treatments according to:

$$Max \sum_{j=1}^{k} \left(Z_j \times \frac{N_j}{A_j} \right) \tag{6}$$

subject to:

$$\sum_{j=1}^{k} (Z_j \times A_j) \le C \tag{7}$$

and

$$T_j \ge T \tag{8}$$

where Z is a vector of binary variables indicating whether the j-th stand is treated (i.e., $Z = 1$ treated and $Z = 0$ untreated), Nj is the objective metric in the j-th stand, A_j is the area of the j-th treated stand, C is a global constraint on investment level per planning area, and T_j is the threshold condition in the j-th stand to trigger a treatment (Ager et al., 2019a). We constrained treatments to 20% of the area of hazardous fuels including both forests and shrublands. Treatment thresholds excluded protected lands and steep slopes (>60%) that restrict operational practices. The *TI* (Appendix B) transmission index grid was used as the objective metric N to prioritize the treatments. Prioritizing based on the rate (i.e., N_j/A_j) rather than just the sum of the objective values in stands (N) allowed us to target smaller-than-average treatment units with high transmission potential.

2.6. Fuel treatment prescriptions

We designed treatments according to local practices (Ager et al., 2019a). Treatments targeted hazardous fuels (dense-shrublands and forest fuels), and were based on fuel model, tree cover and density, and proximity to the WUI. We implemented a broadcast burn in open areas, and a thinning from below plus underburning in forests, except for dense

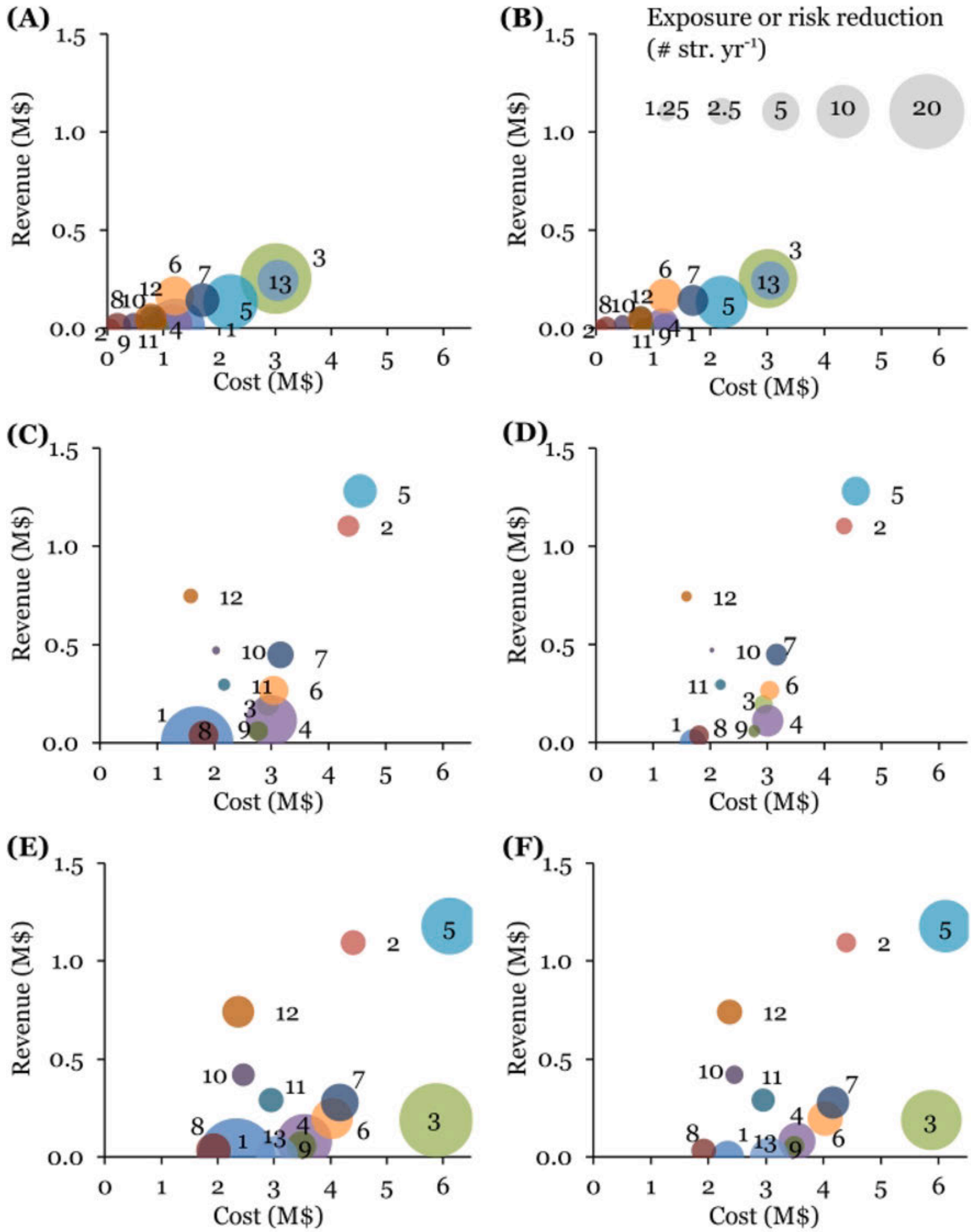

Fig. 6. Fuel treatment cost vs. revenue in the different planning areas for the home ignition zone (A and B), landscape (C and D), and combined (E and F) fuel treatment strategies. The bubble size is the exposure (left panels) and risk (right panels) reduction in terms of the number of structures per year. The points are colored and numbered by planning area (Fig. 2B).

overstocked stands where we combined the thinning with a pile burning (TP). We implemented HIZ surface fuel reduction and thinning treatments in areas adjacent to WUI residential sites. The thinning treatments preferentially targeted fire intolerant species and removed intermediate and codominant trees (diameter at breast height <53.3 cm) to remove the ladder fuels and favor the large upper crown classes (Jain et al., 2012). We assigned the low load compact conifer litter (TL181) fuel model to treated forests and low load broadleaf litter (TL182) to treated shrublands (Scott and Burgan, 2005). Forest stands were thinned to 60% of canopy cover, 4 m of canopy base height, and 0.08 kg m^{-3} of canopy base density (Scott and Reinhardt, 2007). The merchantable thinning volume was estimated at 30-m resolution using the imputed tree list data from Riley et al. (2016) processed with the Forest Vegetation Simulator (Crookston and Dixon, 2005).

2.7. Cost-efficiency analysis

We estimated treatment cost and revenue from thinning to assess

Table 2
Treatment cost and revenue by prescription type for the different fuel treatment strategies. We excluded protected lands as well as slopes >60% from treatment. Revenue was estimated from merchantable products obtained from a thinning.

Prescription (abbreviation)	Average Cost ($ ha^{-1})	Average Revenue ($ ha^{-1})	Landscape treatments				HIZ treatments				Combined strategy			
			Area (ha yr^{-1})	Area (%)	Cost (M$ yr^{-1})	Revenue (M$ yr^{-1})	Area (ha yr^{-1})	Area (%)	Cost (M$ yr^{-1})	Revenue (M$ yr^{-1})	Area (ha yr^{-1})	Area (%)	Cost (M$ yr^{-1})	Revenue (M$ yr^{-1})
BB	515	ns	14,132	23.6	7.16	0.02	1,089	4.8	0.69	0.00	15,016	19.2	7.72	0.03
T	551	106	39,410	65.8	21.61	4.22	1,265	5.6	0.79	0.11	40,492	51.8	22.29	4.31
TP	621	304	1,912	3.2	1.18	0.58	90	0.4	0.07	0.03	1,995	2.6	1.24	0.61
W	750	ns	2,136	3.6	1.59	0.01	9,659	42.8	7.26	0.03	9,961	12.7	7.46	0.03
WT	744	147	2,272	3.8	1.58	1.58	10,453	46.3	7.86	0.93	10,692	13.7	7.99	0.94
Total	636	186	59,862	100	33.12	6.41	22,556	100	16.67	1.09	78,155	100	46.69	5.91

cost-efficiency, defined here as the economic investment required to reduce exposure and risk one structure unit per year. The fuel treatment cost was estimated as detailed in Berry et al. (2006) based on fire regime, treated area, dominant fuel type, season, topographic variables, and types of prescribed burns (broadcast burn, underburn, and WUI) for the risk reduction objective. Cost estimates were updated to current conditions based on price inflation and provided as a 30-m resolution grid to capture the complex patterns across the study area. We estimated revenue using merchantable thinning volume and the market price on public sales made in the Payette Lakes Ranger District during the 2019 fiscal year (DOL, 2019). We considered sawlog volume and stumpage price for the main species, including $88 MBF^{-1} for ponderosa pine (*Pinus ponderosa*), $121 MBF^{-1} for Douglas-fir (*Psuedotsuga menziesii*), $109 MBF^{-1} for grand fir (*Abies grandis*), and $126 MBF^{-1} for lodgepole pine (*Pinus contorta*). We calculated the immediate exposure and risk reduction the next year after the treatment implementation, and the costs reflected the entire duration of the treatments (i.e., the costs were not annualized).

3. Results

3.1. Area treated by landowner and prescription

The area and proportion of treatments allocated to different land tenures varied within the planning areas and across our three fuel treatment scenarios (Fig. 3). The area treated was 59,862 ha for the landscape fuel treatment, 22,556 ha for HIZ, and 78,155 ha for the blended scenario combining HIZ and landscape treatments. Overall, most treatments were located on private and USFS lands (>70% of treated area), with some variability among the planning areas. BLM and SDOL lands constituted 10–25% of treated area in most planning areas. Other landowners (i.e., SPR and SFW), accounted for <3% of treated area. As expected, most landscape and combined scenario treatments were on USFS lands, whereas treatments on private lands were predominantly within the HIZ scenario. The combined fuel treatment scenario presented the most balanced treatment allocation between the land tenures. Most planning areas contained variable vegetation types in different proportions (Fig. 1A); however, exceptions included treated areas on BLM lands in planning area 1 and shrubland patches within USFS forested lands in planning area 2.

Prescription types varied substantially among the different planning areas (Fig. 4). The broadcast burn and thinning plus underburn were the dominant treatment types varying dependent on vegetation type. While the thinning plus underburn was the prevalent prescription in the planning areas located in the northern and eastern portion of the study area, broadcast burn was the principal treatment in planning areas in the southwestern plains. Broadcast burn was the dominant treatment prescription (>50% of the area) in planning areas 1, 4, and 9 for the landscape and combined scenarios. Overall, the WUI treatment prescriptions were prevalent in the HIZ treatment scenario (Fig. 4C and D). The WUI treatments required a thinning (i.e., WT prescription) that ranged between 40 and 60% of the treated area in most planning areas. Some of the landscape fuel treatments also corresponded to WUI treatment prescription types and showed that 5–15% of high-transmission areas in planning areas 1 and 4 were located in the WUI. The thinning plus underburn and pile burning was a minor prescription except for planning area 12, where this prescription was assigned to 15% of treated stands.

3.2. Predicted structure exposure and loss

Predicted structure exposure and loss varied widely among the communities in the study area (Table 1). The predicted number of exposed structures under current conditions was 211 per year, which is 0.33% of the total number of structures (n = 63,707) in the study area. The bulk of exposure (>55%) was concentrated in the communities of Emmett, McCall, Council, and Cascade, where the values ranged between 18 and 52 structures per year. Eight communities had <5 exposed structures per year. As expected, we observed the sharpest decrease in exposure as a result of treatments implemented in the highest transmission areas. Overall, total predicted exposure was reduced by 23%, 37%, and 47%, respectively, for the landscape scale, HIZ, and the combined scenarios. Structural loss, which was predicted at 82 structures per year (0.13%) under the no treatment scenario, was reduced by 22%, 62%, and 69%, respectively, for the landscape scale, HIZ, and the combined strategies respectively. McCall had both high exposure and high loss (17.8 str. yr^{-1}) whereas Emmett showed a substantial reduction from 51.9 exposed structures per year to 5.9 lost structures per year. This is explained by the substantial differences in wildfire hazard in the HIZ and shows that high exposure does not necessarily translate into a high loss. While a few communities presented values higher than 10 structures per year in the landscape fuel treatment scenario, expected loss was less than 5 structures per year in the HIZ and combined scenarios. Expected loss values within communities exhibited complex patterns, although in general, we observed increased exposure and loss closer to the community core. Densely developed WUI areas at the outskirts of community cores had the highest predicted exposure, but it is worth noting that high exposure did not necessarily equate to high loss (Fig. 5).

3.3. Cost-efficiency

Treatment cost and revenue per unit of exposure treated showed substantial differences among planning areas and scenarios (Fig. 6). In

Table 3
Treatment cost-efficiency in terms of required treatments (ha yr^{-1}) and net cost ($ yr^{-1}) to reduce exposure and the expected loss by one structure by planning area (PA; Fig. 2B). Results for planning areas other than those where we implemented landscape treatments are summarized as planning area 13. The net economic cost was estimated as the difference between the fuel treatment cost and revenue from thinning. The revenue is presented as the percentage of the cost to understand the contribution of timber sales in covering the treatment cost. We treated 59,862 ha in for the landscape treatment scenario, 22,556 ha in the home ignition zone scenario, and 78,155 ha for the combined scenario.

PA	Landscape treatments					HIZ treatments					Combined strategy				
	Revenue (% of cost)	Exposure (ha $str.^{-1}$)	Exposure ($ $str.^{-1}$)	Loss (ha $str.^{-1}$)	Loss ($ $str.^{-1}$)	Revenue (% of cost)	Exposure (ha $str.^{-1}$)	Exposure ($ $str.^{-1}$)	Loss (ha $str.^{-1}$)	Loss ($ $str.^{-1}$)	Revenue (% of cost)	Exposure (ha $str.^{-1}$)	Exposure ($ $str.^{-1}$)	Loss (ha $str.^{-1}$)	Loss ($ $str.^{-1}$)
1	0	120	264,026	853	631,606	0	99	189,212	400	392,846	0	133	361,778	750	597,413
2	25	4,414	1,718,314	7,487	3,248,246	7	89	33,645	111	73,672	25	3,321	1,750,804	5,269	2,307,201
3	7	2,871	165,191	4,014	2,067,414	8	222	166,420	325	221,705	3	465	343,187	706	432,834
4	4	607	409,713	1,563	777,499	2	299	162,073	461	310,562	2	598	490,164	1,311	691,042
5	28	1,963	250,601	2,625	1,069,073	6	268	158,373	304	210,317	19	859	378,562	988	480,441
6	9	1,741	405,685	4,113	2,075,924	14	297	151,800	380	243,411	5	1,100	560,876	1,525	859,004
7	14	2,334	465,525	3,498	1,551,662	8	627	267,004	751	446,088	7	1,488	666,934	1,960	994,585
8	2	970	605,986	2,109	1,177,679	4	101	58,979	178	118,082	2	763	645,462	1,548	875,165
9	2	3,810	1,005,893	10,213	4,991,515	0	426	314,329	820	584,857	2	2,032	1,275,730	4,297	2,254,067
10	23	14,455	756,420	35,588	15,293,313	5	403	214,530	603	403,142	17	2,196	984,570	3,489	1,673,512
11	14	7,271	657,308	9,332	4,354,883	7	549	256,695	587	389,762	10	2,290	930,214	2,574	1,338,334
12	47	3,613	281,438	6,731	1,931,669	6	278	244,194	446	313,005	31	1,061	541,965	1,713	698,848
13	0	0	0	0	0	0	643	254,120	751	528,340	0	622	276,353	724	553,887
Avg.	15	1,213	341,525	3,353	1,573,988	7	292	189,396	440	304,234	10	780	512,161	1,374	741,021

general, revenue was higher in the areas with the highest cost except for planning area 12 (Fig. 2), where costs were low relative to revenue. Revenue was relatively low for the HIZ strategy because of lower tree density and basal area in treated stands. On average, thinning treatments in the HIZ scenario provided 4.5 times lower merchantable timber volume than in forest stands compared to the landscape treatment scenario. Notably, higher treatment cost was not correlated with higher exposure and expected loss (Fig. 6), and some planning areas with relatively high exposure had low costs relative to other planning areas (e.g., planning area 1). Overall, revenue was about 10 times lower than cost, although a few planning areas generated revenue approaching 24% of the cost. Except for planning areas 1 and 4, where estimated wildfire transmission to communities was relatively high, the HIZ scenario (Fig. 6A and B) was much more effective than the landscape fuel treatments at reducing exposure and expected loss (Fig. 6B and C). For instance, planning area 3 had a predicted reduction in exposure and loss for the HIZ scenario that was almost 10 times higher than the landscape fuel treatment scenario.

Treatment cost varied substantially by prescription type and distance to developed areas (Table 2). While thinning plus underburn was the most extensive landscape scenario prescription (>50% treated area), WUI surface fuel reduction resulted in the most common treatment in the HIZ scenario. The highest cost corresponded to the WUI treatments, with an average cost of $750 per ha; broadcast burn in open areas was the lowest cost, with an average price of $515 per ha. Pile burning to eliminate logging slash increased costs about 12% compared to areas requiring thinning and underburns. Thinning revenue from overstocked stands averaged $304 per ha, or about half of the average cost ($621 ha^{-1}). Revenue from thinning in HIZ areas accounted for only 20% of the average cost.

From a cost-efficiency perspective, the HIZ scenario had the highest exposure and risk reduction per unit area treated and cost (Table 3). On average, the HIZ scenario reduced exposure and loss per structure by treating 292 and 440 ha per year, respectively, and required $189,396 and $304,234 per year, respectively for the cost of the treatments. However, planning area 3 was an exception where the landscape scenario was more cost-efficient than HIZ. The planning area with the highest HIZ treatment performance treated 89 ha per year (with a $33,645 yr^{-1} cost) and 111 ha per year (with a $73,672 yr^{-1} cost) to reduce exposure and loss by one structure. Nonetheless, the combined solution resulted in the highest reduction in exposure, where treatments on just 5.7% of the study area reduced exposure by 47.5% (100 structures yr^{-1}) and loss by 69.1% (57 structures yr^{-1}). As expected, the landscape fuel treatment scenario resulted in the highest revenue from thinning, with an average contribution between 15% and 47% of the maximum required economic investment. Planning areas where open woodlands and shrubby fuels were dominant had the lowest treatment cost and revenue, in general. The total cost was $33.1 million per year for the landscape fuel treatment scenario, $16.7 million per year for the HIZ scenario, and $46.7 million per year for the combined treatment scenario.

4. Discussion

This study compared scenarios that targeted exposure and loss from alternative treatment strategies at different scales and highlights the potential benefits of a multi-scale approach to community risk reduction. Overall, we found that the HIZ treatments were more cost-effective (i.e., highest reduction in exposure and loss per $ invested in fuel treatments), and landscape treatments that targeted high-transmission areas on top of HIZ treatents (i.e., combined strategy) reduced predicted exposure and loss by an additional 19% (Table 1). Despite this general finding, the results showed complex spatial patterns for predicted exposure and loss that resulted from multi-scale interactions among simulated fires, and conditions in the HIZ that affected probability of exposure and loss. These patterns strongly influenced the

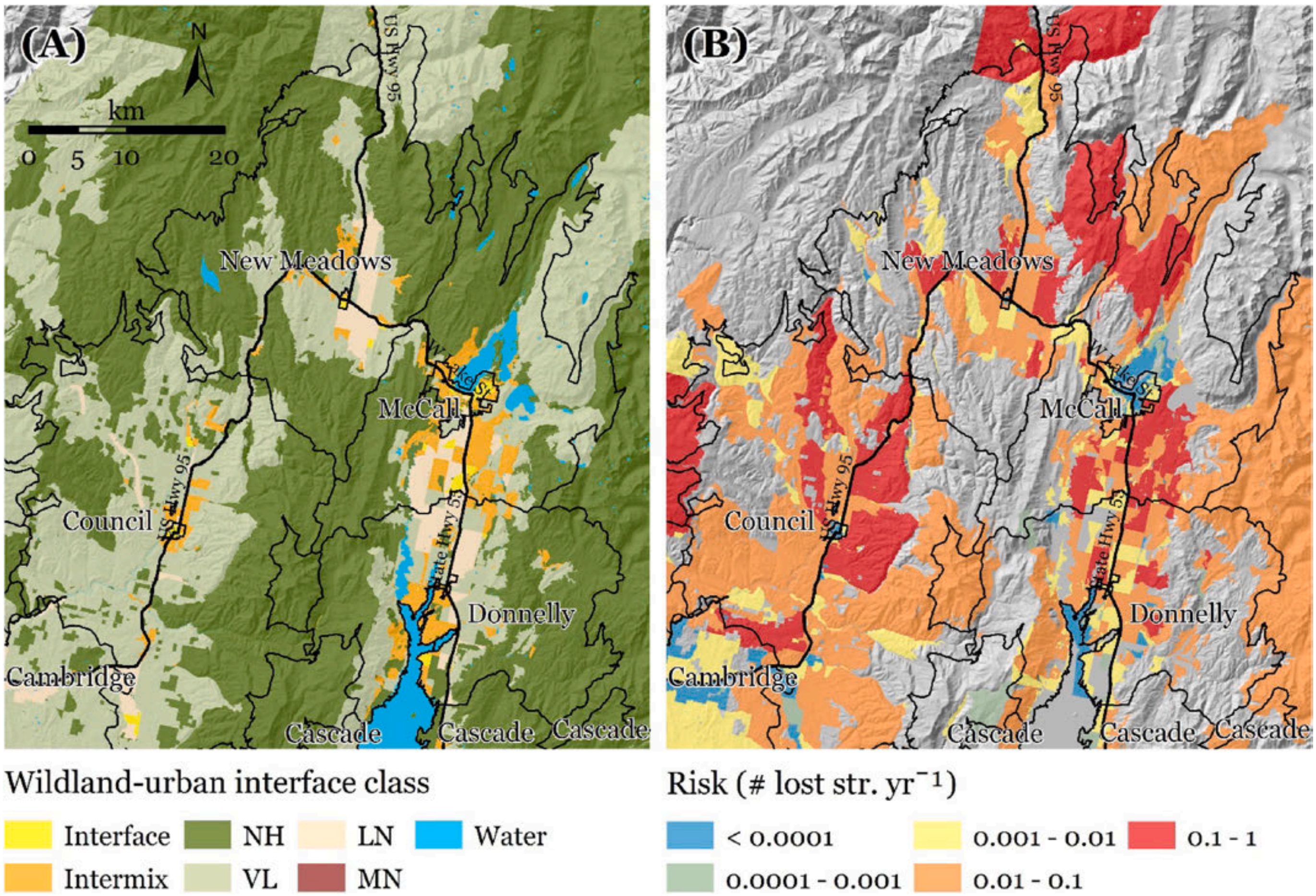

Fig. 7. Wildland-urban interface SILVIS classes (A) (Martinuzzi et al., 2015), and (B) risk assessment results for the northern portion of the study area for current conditions. Our results reveal substantial discrepancies between WUI classes (interface and intermix) and high-risk locations. NH = no housing vegetated; LN = low and very-low housing density; VL = low and very low housing density; MN = medium, and high housing density.

treatment leverage in the modeled scenarios in terms of both area treated and cost, such that in some planning areas HIZ treatments were not as efficient as the other scenarios. Our study replicates the scale of project implementation, making it possible to detect exceptions to this trend and potentially design high resolution, custom mitigation strategies that reflect local exposure and predicted loss. The local patterns of treatment efficiency would not have been revealed with discrete polygon based WUI classes (e.g., SILVIS intermix, interface) used in many prior studies of structure loss, and therefore the methods provide significant advancement in the predictive modeling of wildfire impacts to peri-urban and rural communities. Variability among planning areas in terms of the treatment efficiency, as measured by both financial and per area leverage, reinforces the idea that mitigation strategies are site specific, and generalized conclusions about what WUI density is at highest risk of loss (Kramer et al., 2019) and the most efficient treatment strategies should be applied to local planning problems with caution. Both landscape and HIZ fuels characteristics combined with structure density patterns are significant factors affecting structure exposure and loss (Ager et al., 2021a).

Our modeling predicted that public lands (i.e., Forest Service, BLM, and SDOL; Fig. 3) contributed 37% of exposure to communities, but exposed structures within these large land tenures accounted for just 7% of the total within the study area. Conversely, community cores and developed areas in the WUI contain more than 90% of the exposed structures but contributed relatively little to annual wildfire transmission (<22%). This contrast emphasizes that fires burning populated WUI areas mostly originated elsewhere, as also found in other studies (Haas et al., 2015). Since the bulk of the predicted exposure to communities (85% exposed str. yr^{-1}) in our study was concentrated in a small portion of the landscape (25% of the area), it is possible to target a relatively small portion of the landscape for treatments as part of federal forest restoration programs and potentially improve the efficiency of landscape treatment strategies (Fig. 4). Our treatment locations were specific to individual planning areas based on predicted fire transmission to developed areas and individual structures. Overall, we found landscape fuel treatments alone within these high-transmission areas reduced annual exposure by 23%, or about 5% of exposure reduction for every percentage of hazardous fuel area treated in the study area.

Despite the wide variability among strategies and between planning areas, and higher treatment cost, HIZ treatments resulted in the most cost-efficient scenario for the study area as a whole. Financing these treatments will likely require both investments by homeowners and funding from federal agencies as identified in the Infrastructure Investment and Jobs Act (U.S. House of Representatives, 2021). We estimated fuel treatment costs at about \$5 to \$25 yr^{-1} per structure, considering all structures such as individual structures and apartment buildings, or \$6 to \$29 yr^{-1} per resident (US Census Bureau, 2019). These costs ignore substantial structural improvements required for many structures to reduce their susceptibility to wildfire (Mell et al., 2010). It is important to recognize that the lower cost-efficiency of risk mitigation in the landscape scenario does not diminish the importance of restoration on the surrounding fire excluded forests to improve fire resiliency and long-term community adaptation to wildfire. Federal forest restoration programs can contribute significant revenue and provide multiple social and ecological benefits (Stephens et al., 2021).

Prior empirical studies have identified specific WUI classes (e.g., intermix, interface) that account for the bulk of the loss (Kramer et al., 2019). In these studies the results are presented in classes, where typically wildland vegetation is binned into large groups (Kramer et al., 2019; Mietkiewicz et al., 2020a). With newer MS building footprint data (Microsoft, 2018), the prediction of structure exposure and loss can use structure-scale explanatories rather than densities of structures and average conditions. With the older census block data, structure clustering and site specific fuels are not known, making it difficult to disentangle the gradient of burnable fuels and its effect on exposure (Ager et al., 2021a). Therefore, prioritizing WUI treatments requires high-resolution maps capturing the intricate risk patterns. Management decisions based on existing WUI class maps alone might not always capture fine-scale variation in the drivers of building loss (Fig. 7).

We recognize multiple limitations related to use of fire simulations for predicting structure exposure and loss, and the cost and benefits of the treatments, all contributing to uncertainty in the results. On the positive side, the sample size of wildfire events provided by the simulation and the precise building footprint data made possible a reasonable characterization of fuels and potential fire behavior in the HIZ. However, predicting loss from exposure is coarse at best, given that localized factors in time and space during fire events can determine the survival or loss of a structure. Accurately replicating the type of restoration and field management prescriptions across multiple forest owners in large study areas is a complex problem (Charnley et al., 2017), and contributes uncertainty in the revenue calculations. Our treatment cost values agreed with the estimates in ongoing shared stewardship programs as derived from the local Forest Service administrative units. Although our models were parameterized with the best available data, given the specific research questions, significant gaps exist with the prediction of structure loss using coarse models developed from other regions. It is important to note that we simulated HIZ treatments in all of the communities, whereas targeting only WUI areas with the highest exposure would likely substantially increase treatment cost efficiency.

5. Conclusions

Restoration of fire excluded landscapes in concert with community-scale investments to reduce catastrophic impacts is a well-recognized goal in public policies (USDA Forest Service, 2015). We identified the tradeoffs between alternative, multi-scale treatment strategies that connected community and landscape scales of risk, a necessary step to make progress in reducing wildfire losses in developed areas. This work demonstrates the potential value of tightening linkages between community protection plans (CWPP Task Force, 2008; Jakes and Sturtevant, 2013) and forest restoration strategies within the community fireshed (Ager et al., 2015, 2021b), by identifying linkages between land tenures transmitting fire and finely grained small properties in the WUI where loss is concentrated (Ager et al., 2015). As risk assessment technology and data continue to improve, models that bridge fire behavior across scales from landscapes to structures will substantially improve predictive capabilities. Advancements in machine learning and remote sensing will provide building-specific vulnerability data that will substantially improve the prediction of loss (Bardeloza et al., 2019). These data coupled with ember production models will help link the mechanics of landscape-scale fire spread with structure ignition in developed areas. Additional enhancements in technology and data will likely provide a foundation of tools to design community-specific mitigation programs in concert with federal and state restoration programs in the surrounding landscapes.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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