PREDICTED FIRE BEHAVIOR AND SOCIETAL BENEFITS IN THREE EASTERN SIERRA NEVADA VEGETATION TYPES

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ABSTRACT

We investigated potential fire behavior and various societal benefits (air pollution removal, carbon sequestration, and carbon storage) provided by woodlands of pinyon pine (*Pinus monophylla*) and juniper (*Juniperus californica*), shrublands of Great Basin sagebrush (*Artemisia tridentata*) and rabbitbrush (*Ericameria nauseosa*), and recently burned annual grasslands near a wildland-urban interface (WUI) community in the high desert of the eastern Sierra Nevada Mountains. Fire behavior simulations showed that shrublands had the greatest flame lengths under low wind conditions, and that pinyon-juniper woodlands had the greatest flame lengths when winds exceeded 25 km hr^{-1} and fire transitioned to the crowns. Air pollution removal capacity (PM10, O_3, NO_2, etc.) was significantly greater in pinyon-juniper stands, followed by shrublands and grasslands. Carbon storage (trees and burned tree snags only) did not significantly differ between pinyon-juniper and burned stands (~14 000 kg ha^{-1}), but will change as burned snags decompose. Annual C sequestration rates in pinyon-juniper stands averaged 630 kg ha^{-1} yr^{-1}. A landscape-level assessment showed that total compliance with residential defensible space regulations would result in minimal impact to air pollution removal capacity and carbon sequestration due to a currently low population density. Our methodology provides a practical mechanism to assess how potential management options might simultaneously impact both fire behavior and various environmental services provided by WUI vegetation.

Keywords: air pollution removal, *Artemesia tridentata*, carbon sequestration, fire behavior, FlamMap, NEXUS, *Pinus monophylla*, UFORE, wildland-urban interface

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INTRODUCTION

Burgeoning population growth are affecting fire prone areas in southwestern ecosystems. This trend further exacerbates difficulties in fire management in the region, which has been complicated by a changing climate that has increased the length and severity of fire season (Westerling *et al.* 2006), and by invasive species that can significantly alter fire regimes (Brooks *et al.* 2004). Because of mounting suppression costs and private property losses associated with fires in the wildland-urban interface (WUI), there is an escalating call there and throughout the western United States to significantly reduce vegetation both around structures and across the landscape to mitigate the risk of homes burning (Dombeck *et al.* 2004).

Native vegetation, however, is more than fuel for fire, providing various levels of tangible and intangible benefits to society. For example, vegetation not only enhances community attractiveness and subsequent value, but also removes air pollution (Taha *et al.* 1997), which regularly follows urbanization (Fenger 1999). Further, vegetation sequesters and stores atmospheric carbon, which many believe to be a leading cause in global climate change (Solomon *et al.* 2007).

Thus, land managers are beset with the paradox that vegetation is both a liability and an asset to residents living in the WUI. Unfortunately, fuels management is sometimes accomplished with little regard to the impact to the multiple societal and environmental benefits that vegetation provides. However, sustainable land management necessitates recognizing various tradeoffs when modifying vegetation (Dicus and Zimmerman 2007), understanding that post-treatment vegetative composition and structure will influence both potential fire behavior and benefits such as absorbing stormwater runoff, removing air pollutants, and sequestering and storing C (Dicus 2008).

Minimizing both destructive wildfires and loss of vegetative benefits are competing, yet integral, objectives in the WUI. We sought to provide a simultaneous evaluation of potential fire behavior and various benefits provided by the predominate woodland, shrubland, and grassland vegetation types near Kennedy Meadows, California, USA, a WUI community in the high desert of the eastern Sierra Nevada Mountains in California. Further, we explored how implementation of various defensible space standards could potentially affect risk of home ignitions and loss of vegetative benefits to the community.

METHODS

Study Area

Kennedy Meadows is an isolated, rural community located at an elevation of ~1980 m in the eastern Sierra Nevada along the south fork of the Kern River in the southeast corner of Tulare County, California (36°01'26" N, 118°06'55 W). There are approximately 50 permanent residents and 176 structures in the community, which range from high-value homes to abandoned trailers. Vegetation within and immediately surrounding the community consists of three primary types: woodlands consisting largely of single-leaf pinyon pine (*Pinus monophylla*) with a small component of California juniper (*Juniperus californica*); shrublands dominated by Great Basin sagebrush (*Artemisia tridentata*) and rabbitbrush (*Ericameria nauseosa*); and annual grasslands with prolific pinyon pine and juniper snags that resulted from the Manter Fire, which occurred in 2000.

The only documented record of fires burning in the area include the Manter Fire, which burned ~30 000 ha (including 712 ha in the Kennedy Meadows community), and the 2003 Michael Fire, which burned ~120 ha east of the community. However, a mosaic of younger pinyon-juniper stands, usually less than 20 ha, are readily visible in the surrounding mountains, indicative of extensive past fire activity in the area. The Manter Fire is especially singed into the conscience of Kennedy Meadows' residents because it was a large, high-intensity, high-severity crown fire that destroyed eight homes in the southern portion of the community. Further, the post-fire landscape has shown minimal vegetative regrowth to date, which, while not abnormal in pinyon pine (Wangler and Minnich 1996), serves as a constant reminder of the potential threat of wildfire to the community.

Field and Modeling Methods

We installed three randomly located 0.0405 ha plots in each of the primary vegetation types (pinyon-juniper, shrubland, and burned areas that are now grasslands with standing snags) to collect data pertinent to both fire behavior simulations and vegetative benefit calculations. We avoided minor features such as localized rock outcrops and bogs. Tree data collected included species, diameter at breast height, total height, and height to base of the live crown. Shrub data included species, canopy height, canopy width, and percent dead. Snag data included species, diameter at breast height, and height. All trees and snags found in plots were greater than 1.4 m and were thus sampled for diameter at breast height. We also made ocular estimates of overstory canopy coverage (percent of plot occupied by trees and by shrubs) and ground cover (percent of plot covered by bare soil, by litter or duff, and by grass).

We modeled potential fire behavior at both the stand level for each of the three vegetation types and at the landscape level across the Kennedy Meadows community. We assigned fuel models to each of the three vegetation types based on how fuelbed measurements and observations in the vegetation plots compared with standard fuel model loadings, descriptions, and photo guides (Ottmar *et al.* 2000, Scott and Burgan 2005). We designated pinyon-juniper woodlands as TU1 (low load, dry climate timber-grass-shrub), shrublands as GS2 (moderate load, dry climate grass-shrub), and burned areas as GR1 (short, sparse dry climate grass).

All geographic information system (GIS) data necessary for landscape-level simulations and for calibration of weather inputs were supplied by the Southern Sierra Geographic Information Cooperative (A. Birkholz, Sequoia and Kings Canyon National Parks, unpublished data; hereafter SSGIC). Elevation was obtained from a Digital Elevation Model (DEM). Slope and aspect files were then derived from the DEM with ESRI® ArcMap™ (version 9.1). We converted fuel models, canopy cover, and canopy base heights in the original data layer as necessary to reflect field measurements and observations. All gridded raster data layers were 30 m × 30 m.

Weather, wind, and fuel moisture parameters utilized in fire behavior simulations were intended to reflect a scenario similar to that experienced in the 2000 Manter Fire. Existing documentation of the Manter Fire included general ranges of temperature, relative humidity, and winds; a specific National Fire Danger Rating System Burning Index (BI); and a fire progression map (S. Williams, Sequoia National Forest, personal communication). We therefore used a multi-step process to generate and then calibrate specific weather, wind, and fuel moisture inputs based on the available data. First, we estimated fine fuel moisture values using the reported weather conditions and standard fuel moisture tables (Rothermel 1983). We then adjusted specific weather and fuel moisture inputs, while remaining within the general documented range, within the NFDRS Calculator of FireFamily Plus 3.05 (Rocky Mountain Research Station Fire Sciences Lab and Systems for Environmental

Management 2002) until the specific BI reported for the Manter Fire resulted.

To further calibrate the specific inputs, we used FARSITE 4.1.03 fire simulation software (Finney 1998) to compare simulated fire behavior with documented fire behavior. Based on weather, wind, and fuel moistures derived from FireFamily Plus (Table 1), and GIS data obtained from SSGIC, fire spread and behavior in the FARSITE simulations were relatively consistent with the Manter Fire spread map and documented fire behavior. Subsequent minor adjustments in weather and fuel moistures caused negligible changes in simulated fire spread and behavior, thus we considered the original generated values appropriate for stand- and landscape-level fire simulations in the present study.

We considered this multistep approach to generate specific fire simulation inputs appropriate because it incorporated all available data and because of commonalities in the derivation of BI and the fire behavior outputs calculated in the present study. BI is linearly related to flame length and is a modified version of Byram's (1959) flame length equation (Bradshaw *et al.* 1983). Both Byram's (1959) flame length equation and Rothermel's (1972) spread equation, which is the foundation of simulated outputs in the present study, require similar sets of inputs, including fuels, weather, and topography.

We used NEXUS 2.0 (Scott and Reinhardt 2001) for the stand-level simulations because of its ability to predict both surface and crown fire behavior. We calculated rate of spread and flame length for each vegetation type across a range of open wind speeds while holding all fuel parameters and slope constant (see Table 1 for input values).

We used FlamMap 3.0 (Finney 2006) to assess potential fire behavior at the landscape-level. Although FlamMap uses the same spatial and weather data as FARSITE, FlamMap is considered more useful to examine potential fire behavior at any given point across a landscape, which is preferable when assessing potential fire hazard in an area (Stratton 2004). Initial fuel moistures (Table 1) were conditioned across the landscape for two days to adjust for differences in elevation, aspect, and overstory canopy shading across the study area that would affect fuel moisture at any given point (Nelson 2000). We simulated potential fire behavior at the most extreme part of the day and winds were forced to blow uphill across the landscape to simulate worst-case conditions at any given point. We ran two simulations, including no wind and 40 km hr^{-1} winds (at 6 m above canopy); the latter was intended to represent conditions experienced during the Manter Fire.

Table 1. Inputs used in fire behavior simulations. Stand-level simulations utilized worst case scenario conditions. Landscape-level simulations subjected initial fuel moistures to a 2-day conditioning period.

	Value
Weather inputs	
Wind speed (km hr^{-1})	40
Wind reduction factor	0.3
Low temperature (^{o}C)	13
High temperature (^{o}C)	35
High relative humidity (%)	30
Low relative humidity (%)	10
Fuel moisture (%)	
1 hr	4
10 hr	5
100 hr	6
Live herbaceous	60
Live woody	75
Foliar moisture	100
Canopy characteristics	
Height (m)	4.6
Canopy base height (m)	0.6
Canopy bulk density (kg m^{-3})	0.1
Available canopy fuel load (t ha^{-1})	5.4

Societal benefits, including pollution removal, C storage, and C sequestration, were calculated by the Forest Service Northeastern Research Station (R. Hoehn, Forest Service, personal communication) using the Urban Forest Effects Model (Nowak and Crane 2000; hereafter UFORE), utilizing data collected in the 0.0405 ha vegetation plots. UFORE calculates whole-tree current C storage for individual trees based on allometric equations in the literature (Nowak and Crane 2002), utilizing field observations of species, diameter at breast height, tree height, height to live crown, average crown width, and percent dieback. UFORE then calculates annual C sequestration using current biomass estimates in conjunction with tree growth equations in the literature, which are adjusted dependent on tree condition. UFORE does not currently estimate C storage or sequestration for shrubs (R. Hoehn, Forest Service, personal communication). UFORE also calculates hourly removal of ozone (O_3), sulfur dioxide (SO_2), nitrogen oxide (NO_2), carbon monoxide (CO), and particulate matter less than 10 µm (PM10) based on a canopy deposition model (Baldocchi *et al.* 1987) that depends on plant leaf area derived from equations in the literature and on local weather and air pollution data (Nowak 1994, Nowak and Crane 2000). Each of the calculated benefits was converted to a per-hectare basis. We used one-way ANOVA ($\alpha = 0.05$) followed by Tukey pairwise comparisons (MiniTab version 15.1.20.0) to compare means across vegetation types for each of the calculated benefits.

We then calculated each of the societal benefits across the entirety of the Kennedy Meadows landscape by multiplying per-hectare benefits for each vegetation type by the total area of each vegetation type (as calculated by ArcMap). To illustrate the potential effects of legally mandated defensible space regulations on societal benefits (California Public Resources Code 4291), we ran two defensible space scenarios: one with 9.15 m buffers (representing 1991 standards) around each of the 176 structures in the landscape, and one with 30.48 m buffers (representing 2006 standards). In each scenario, we reduced the landscape-level area of each vegetation type by their respective amounts in each buffer.

RESULTS

Shrublands demonstrated both the highest rates of spread (Figure 1) and flame lengths (Figure 2) except when fire in pinyon-juniper transitioned into crown fire as winds increased beyond 25 km hr^{-1} (torching index = 27 km hr^{-1}, crowning index = 43.6 km hr^{-1}). Indeed, pin-

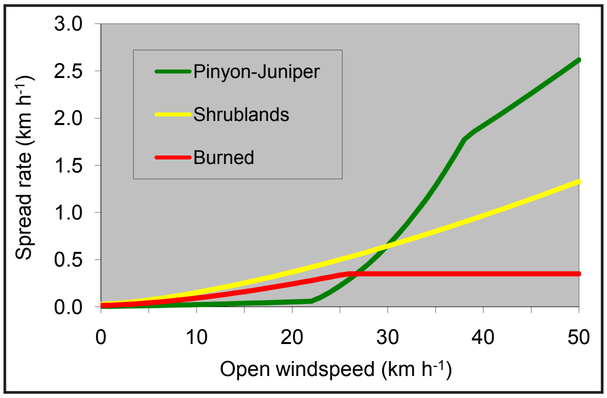

Figure 1. Simulated rates of spread (km hr^{-1}) of pinyon-juniper woodlands, sagebrush-rabbitbrush shrublands, and recently burned annual grasslands in Kennedy Meadows, California.

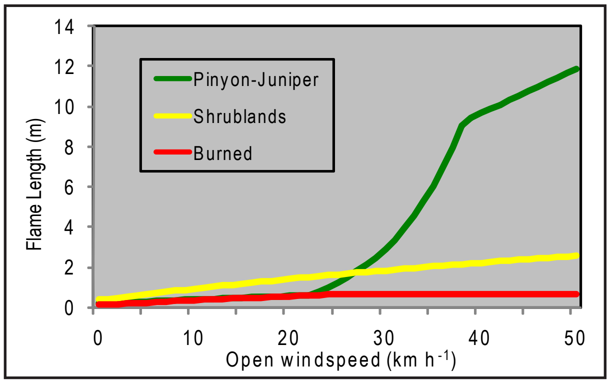

Figure 2. Simulated flame lengths (m) of pinyon-juniper woodlands, sagebrush-rabbitbrush shrublands, and recently burned annual grasslands in Kennedy Meadows, California.

yon-juniper stands demonstrated similar flame lengths as the previously burned stands (flame lengths <0.5 m) until crown fire transition, in which simulated flame length exceeded 10 m. Capacity to effectively model fire behavior in burned areas was exceeded at ~25 km hr^{-1}. Of note, Kennedy Meadows structures are clustered in areas that experience relatively benign fire behavior with low winds (Figure 3), but would facilitate extreme fire behavior under high wind conditions (Figure 4), which historically occur in the area.

Pinyon-juniper stands removed significantly more air pollutants than did shrublands, and shrublands removed more than burned areas (Figure 5). CO was the only pollutant that did not vary between pinyon-juniper and shrublands. Burned areas provided few, if any, measured benefits in terms of air pollution removal.

Mean carbon storage did not vary between pinyon-juniper and burned stands, but vastly exceeded that calculated in shrublands (Figure 6), illustrating the current inability of UFORE to calculate C sequestration or storage in non-tree vegetation types. Carbon storage, as calculated by UFORE, ranged from 0 in some shrubland sites to a high of 16 478 kg ha^{-1} in the densest pinyon-juniper stand. Mean annual C sequestration was 630 kg ha^{-1} yr^{-1} in pinyon-juniper stands, but negligible in shrubland and burned stands, due to the lack of trees in the latter vegetation types.

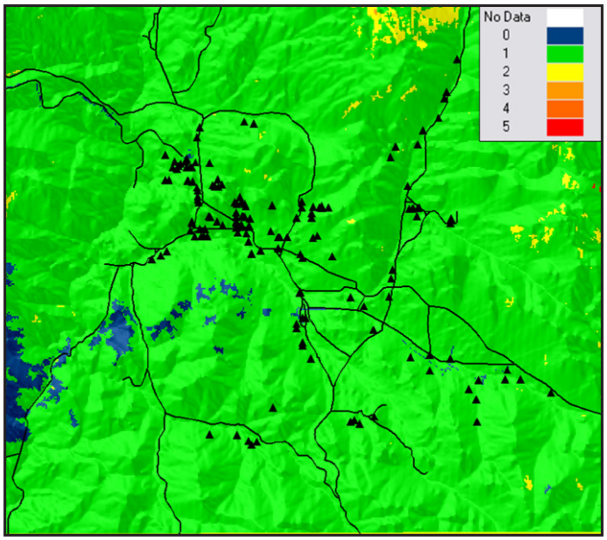

Figure 3. Simulated flame lengths (m) across the Kennedy Meadows community with no winds. Houses represented by black triangles and roads by black lines.

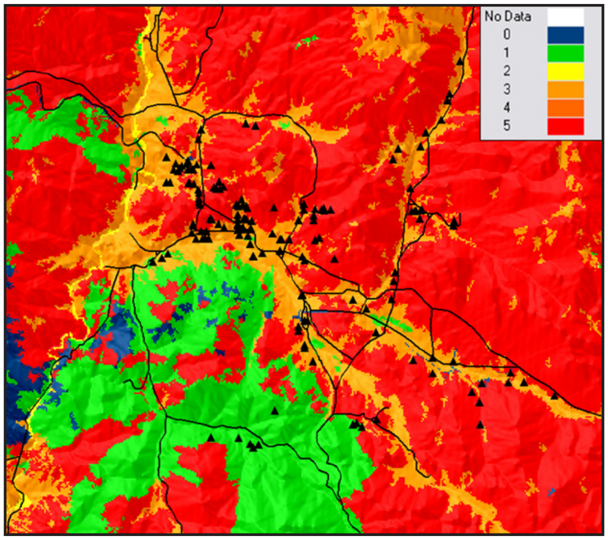

Figure 4. Simulated flame lengths (m) across the Kennedy Meadows community with 40 km hr^{-1} winds (at 6 m above canopy) that were forced to blow uphill at all points across the landscape. Houses represented by black triangles and roads by black lines.

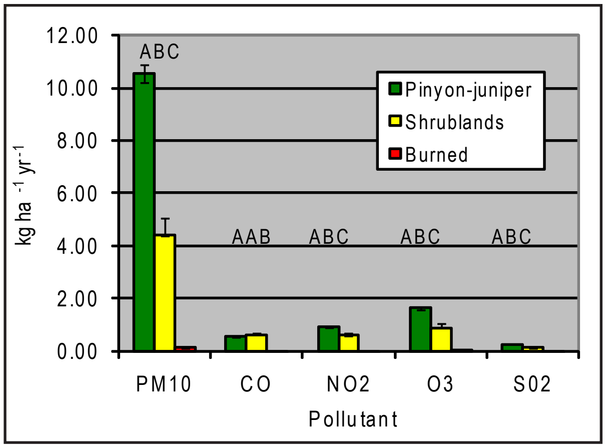

Figure 5. Mean annual air pollution removal capacity (kg ha^{-1} yr^{-1}) in the dominant vegetation types in Kennedy Meadows, California. Bars represent standard errors. Letters represent significance between vegetation types (df = 8, $\alpha = 0.05$).

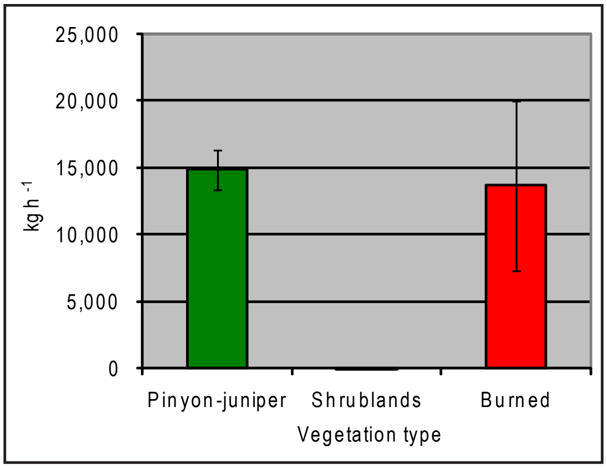

Figure 6. Mean carbon storage (kg ha^{-1}) in the dominant vegetation types in Kennedy Meadows, California. Storage calculations were calculated for tree and tree snags only. Bars represent standard errors. Letters represent significance between vegetation types (df = 8, α = 0.05).

Vegetation across the community removed a total of 567 665 kg of air pollutants per year (Table 2). Total air pollution removal was reduced by 40 kg and 452 kg per year with 9.1 m and 30.4 m buffers, respectively. Carbon storage in trees and burned snags across Kennedy Meadows was 691 427 819 kg (Table 2). Sequestration of C by trees across the community was 22 695 368 kg yr^{-1}. Losses of stored C and C sequestration by creating defensible space buffers were less than 0.05 % of the untreated landscape and were proportional to reductions in pinyon-juniper woodlands.

Table 2. Air pollutant removal capacity, and C storage and sequestration (pinyon-juniper stands only) across the untreated Kennedy Meadows landscape and after 9.15 m and 30.48 m defensible space buffers were placed around 176 structures.

		Treated buffer width	
	Untreated	**9.15 m**	**30.48 m**
Pollutant	**Capacity (kg yr^{-1})**	**Capacity lost (kg yr^{-1})**	**Capacity lost (kg yr^{-1})**
M10	422 338	28	323
CO	26 304	3	28
NO_2	39 477	3	35
O_3	68 098	5	57
SO_2	11 349	1	9
Total	567 566	40	452
Carbon	Total C (kg)	C lost (kg)	C lost (kg)
Stored C	691 427 819	29 135	339 025
Annual C sequestered	22 695 368	1 015	12 005

DISCUSSION

Potential fire behavior in Kennedy Meadows is relatively benign under low wind conditions. Structures adjacent to shrublands would have the greatest risk of structural ignition from flame impingement or radiant heat at low wind conditions. However, under high wind conditions, fires in pinyon-juniper would have the greatest intensity when they transition from surface to crown fires. A similar trend was reported for the Manter Fire, which crowned in pinyon-juniper woodlands during high winds and was reduced in intensity and spread when strong winds abated (Delfino and Dicus 2007). Predicted fire behavior here is consistent with previous studies of pinyon-juniper (Fulé *et al.* 2001) and sagebrush (Sapsis and Kauffman 1991). It must be noted, however, that fire behavior simulations were calibrated for weather and fuel moistures during the 2000 Manter Fire, thus caution must be taken when interpreting fire behavior outside the modeled parameters.

Even a small fire, though, could substantially impact Kennedy Meadows residents due to a myriad of factors. Because of its remote location, fire protection is limited to a summer seasonal fire crew 16 km away, and the small tax base in the area makes expansion of suppression capabilities unlikely (Delfino and Dicus 2007). Further, while residents of rural areas are regularly prepared to protect their individual homes from small fires, many residences are vacation homes that are largely vacant, and therefore unprotected.

Creation of defensible space would likely reduce potential structural ignitions from direct flame impingement or radiant heat transfer (Cohen and Butler 1998). Thus, there is a critical need for fuel treatments, particularly adjacent to structures, to reduce risk of significant fire loss in the community. Most residents, however, have little, if any, near-structure vegetation because they have privacy concerns and a desire to be immersed in natural conditions (Delfino and Dicus 2007). California Public Resources Code Section 4291 has required 9.15 m of defensible space around structures since 1991, which was increased to 30.48 m in 2006. However, inspection of individual homes in Kennedy Meadows is relegated to a small federal fire station, which has never enforced defensible space regulations due to reported lack of personnel.

Even if enforced, it must be noted that defensible space would not impact structural ignition from lofted embers, which is a more critical factor in residential losses than flame impingement or radiant heat (Cohen 2000). To mitigate potential residential losses, California enacted building standards for new construction in areas in which the state has primary fire protection responsibility, effective January 2008 (California Code of Regulations Title 24, Part 2, Section 701.A). While the new standards will likely reduce fire losses in future development, they will not impact vulnerability of existing structures.

On a landscape-level, adherence to defensible space standards would likely have minimal effect on fire size and behavior. While the placement, type, and extent of fuel treatments has been shown to affect fire spread and intensity (Finney 2001, Finney *et al.* 2005, Ager *et al.* 2006), the currently low population density in Kennedy Meadows would likely preclude any significant consequences on the behavior of a large wildfire in the area.

Similarly, defensible space would have little effect on landscape-level vegetative benefits, even if all existing 176 structures in the community conformed to current 30.48 m standards (Table 2). When all pollutants are considered, the previous lower 9.15 m standard resulted in a loss of less than 0.007% total removal capacity, while the more stringent current 30.48 m standard still resulted in a loss of only 0.08% across the landscape.

Likewise, C storage and annual sequestration in the pinyon-juniper stands would also be minimally impacted by enforcing defensible space regulations. Indeed, total compliance of the more stringent defensible space standard would result in losses of only ~0.05 % for both stored carbon and annual carbon sequestered in pinyon-juniper woodlands (339 026 kg yr^{-1} and 12 005 kg yr^{-1}, respectively). This loss could be further lowered by utilizing less intensive fuel treatments such as pruning trees, which would impact the surface fire intensity needed to transition to a crown fires (Scott and Reinhardt 2001) while moderating the effects of total tree removal.

Even though full compliance of defensible space regulations would presently have minimal landscape-level impact to societal benefits afforded by vegetation, managers must still consider the potential cumulative effects of current and future projects. For example, while vegetative air pollution removal is presently not of paramount concern to Kennedy Meadows residents due to currently low concentrations of pollutants, managers are concerned that immigration to the area would simultaneously create more air pollution while removing the vegetative capacity to remove those pollutants. Further, managers concerned about how carbon might impact global climate change should consider the potential tradeoffs in vegetative capacity to sequester and store C versus elevated fuel loading that would facilitate significant fire spread and subsequent losses of stored C (Finkral and Evans 2008).

Unfortunately, none of the commonly used software packages that quantify societal benefits (e.g., UFORE, STRATUM, and CITYgreen) currently estimate C storage and sequestration for non-tree vegetation. Thus, the true impact of defensible space on carbon in the present study cannot be assessed. Further, while UFORE calculates air pollution removal for both trees and shrubs, no benefits of any kind are calculated for grasslands, limiting full interpretation of results. The inability to adequately calculate benefits in shrublands and grasslands is problematic, especially in areas where trees are not the dominant vegetation type (Dicus and Zimmerman 2007). Further, it should be noted that all vegetative benefits calculated by UFORE are based upon equations in the literature. While UFORE attempts to incorporate the most appropriate equations in their calculations (Nowak and Crane 2000), there will undoubtedly be some degree of error in the results. However, while prudence should be taken in acceptance of absolute values, this methodology provides a sound mechanism to evaluate relative differences in benefits for various vegetative communities and for assorted fuel treatment alternatives, especially in landscapes in which trees are the dominant vegetation type.

Kennedy Meadows is emblematic of the challenges that will increasingly vex land managers throughout the fire-prone southwestern United States. Current population projections estimate an enormous influx of residents to the region by 2030. Indeed, compared to 2000 census numbers, Nevada and Arizona are expected to double their populations by 2030, while Utah and Colorado are estimated to increase by 56 % and 35 %, respectively (US Census Bureau 2004).

Continued immigration to previously uninhabited areas will likely result in increased probability of ignitions through accident or arson (Syphard *et al.* 2008), which will serve to increase an ever-escalating cost of federal fire suppression expenditures that has been largely attributed to protection of private property interfaced with public lands (USDA Office of Inspector General 2006, Liang *et al.* 2008). Further, the potential size and severity of wildfires in the region will be exacerbated by warmer and drier conditions (Westerling *et al.* 2006) and fuel accumulation fostered by a century of fire suppression and land use changes (Savage and Swetnam 1990).

Greater risk of loss of life and property in the region will therefore necessitate a greater reliance on fuel treatments to mitigate that risk. Implementation of such treatments would likely be aided by widespread public support in the southwestern United States for prescribed fire and mechanical thinning to ameliorate potential fire hazards (Abrams and Lowe 2005, Ostergren *et al.* 2008). However, as lands are subdivided into increasingly smaller parcels, the potential for effective placement of fuel treatments on a landscape level will become constrained. Additionally, plant communities and the subsequent environmental benefits that they provide will be reduced and fragmented due to land clearing for homes and subsequent supporting services and infrastructure. Land managers must therefore be mindful of these potential losses when implementing fuel treatments in WUI areas.

Our results illustrate how land managers can better evaluate how fuel treatments in WUI areas could potentially affect a community. Our methodology provides a practical mechanism for managers and policy makers to better assess management options for WUI vegetation so as to simultaneously reduce both the risk of fire losses and potential environmental impacts. That said, it is critical to understand that sustainable fire management in the WUI necessitates a holistic approach, including not only elements of vegetation management and suppression capabilities, but also home construction, sound land use planning, and public education (Dicus 2008).

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