

Fuels reduction prescriptions in Sierra Nevada white fir-sugar pine forests: Overcoming Barriers

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Abstract

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Current forest conditions were documented on a 10.2-ha plot in the Yosemite Forest Dynamics Plot (YFDP); a Sierra mixed-conifer forest in Yosemite National Park, California, USA. For live trees ≥ 10 cm dbh in 2009 total tree density was 449 stems/ha, and total basal area was 65.8 m²/ha. *Abies concolor* was the most abundant species, 329 stems/ha, but *Pinus lambertiana* had the highest basal area, 31.7 m²/ha. The high abundance of *A. concolor* increases the risk of an uncharacteristic, high-severity fire in Sierra Nevada mixed-conifer forests. To restore the ecological function of fire in this landscape, the structure of forest must be restored to more characteristic conditions. I make some recommendations for future fuels reduction prescriptions based on the YFDP forest inventory, estimated pre-suppression era structure (reconstructions), and literature review. Because the study site is managed by the National Park Service, and because I recommend mechanical thinning, this ecologically-based fuels reduction prescription may be better suited for Forest Service or private lands. Structural analysis of the YFDP plot reveals that 30-90% of the basal area of *A. concolor* would need to be removed in order to approximate pre-suppression era structure.

Introduction

Recent increases in fire extent and size has been correlated to a warming climate (Westerling et al. 2006). To mitigate this likely increase in high severity wildfires in forests of multiple plant associations, site-specific fuels reduction prescriptions are needed. In much of the Sierra Nevada mixed-conifer forests, white fir (*Abies concolor*) is experiencing recruitment into larger diameters and higher densities because of past forest management practices. Reduction of this high density of fuel loadings can be accomplished with an array of methods including mechanical thinning and prescribed fire (van Wagtendonk and Lutz 2007). Before any work is done however, it is necessary to know what a particular stand's structure was like pre-suppression era. Research has been done to reconstruct past stand structure (North et al 2007, Scholl and Taylor in press). Historic structure can be approximated with mechanical thinning (Knapp et al. 2004), but precise historic structures might not be desirable given the possible futures of climate change (Fulé 2008). Land managers must also be careful in taking site-specific data and applying it to a different region as an exact target. Rather, historic structure estimates provide a general idea of what forest structure and composition was like while an ecologically functional fire regime was present. Scholl and Taylor (in press) examined plots around Yosemite National Park, some as close as 2 kilometers from the Yosemite Forest Dynamics Plot. Thus, there is a unique opportunity to determine what restoration objectives might be regarding the structure and composition of the YFDP (nomenclature follows Hickman 1993).

History and how it led to Current Conditions

Increased fuel loading has created a high-severity fire regime in landscapes that have historically been characterized by frequent, low- and mixed-severity regimes. The overabundance of small diameter stems in dry forests of the U.S. West are a result of past management practices (Keeley and Stephenson 2000, Miller and Urban 2000). As Euro-American settlers migrated west, they caused this landscape-level change fire patterns in three main ways: logging, overgrazing, and fire suppression (Arno and Allison-Brunnell 2002). All of these factors resulted in fire exclusion from the landscape; in forests where fire plays a vital ecological role (Kilgore 1973, van Wagtendonk 2004, van Wagtendonk and Lutz 2007).

Clear cut logging produced even-aged stands that provided continuous fuels which increased the extent of naturally-ignited wildfires. Shade-tolerant species such as *A. concolor* that were historically controlled by a frequent fire return interval were allowed to grow into the spectrum of ladder fuel heights in a more contiguous pattern both horizontally and vertically (Agee and Skinner 2005, Hessburg 2005). The slash that accumulated from logging also promoted future fires by providing a continuous ground fuel.

While perhaps not as influential as the other two causes, over-grazing by livestock is cited as a major contributing factor to uncharacteristically dense forest stocking. Low-lying grass and shrubs move a ground fire through a stand, killing some small saplings. With this understory removed from overgrazing, frequent, low-intensity fires are excluded from the landscape. Without a frequent fire return interval, and without the competition from shrub and grass species, shade tolerant trees were able to grow into higher densities and larger diameters (Arno and Allison-Brunnell 2002). The grazing herds did not browse heavily on the woody trees, so overgrazed forests accumulated uncharacteristically high levels of biomass.

The mixed conifer forests of Yosemite historically experienced a fire return interval ranging from less than 11 years during dry periods to 15 to 30 years during cooler periods; this interval is now between 220 to 270 years for this lower montane zone where the YFDP is located (van Wagendonk and Lutz 2007). Unprecedented, high-severity, stand-replacement fire is increasing in frequency through the U.S. West (McKelvey et al. 1996). Millions of hectares have been affected and are at a higher risk of a stand-replacement fire than they were pre-suppression era (Hessburg et al. 2005). Knowing what events led to these current conditions can help us to prevent the same thing from happening in the future. As fuels continue to accumulate, the costs and dangers of suppressing wildfire increase (Arno and Allison-Brunnell 2002, Snider et al. 2003). If left alone in current conditions, wildfire will self-perpetuate by creating large areas of even-aged stand structure (Healy et al. 2008). It is evident that proactive management is needed to address this issue. Continued suppression of wildfire may be appropriate in some areas such as wildland-urban interfaces, but it should not be used as a landscape-level management tool.

The management goal for old forests should not be to recreate the past perfectly. The future holds uncertain conditions in terms of temperature, rainfall and other resources' availability (Hurteau and North 2008). An adaptive management plan should be developed that considers a future of warmer, drier summers. One component in improving a stand's resistance to increased drought and bark beetle infestations is maintaining or increasing the abundance of *Calocedrus decurrens*. *C. decurrens* is not susceptible to bark beetle infestations (Schwilk et al 2006). Recreating historic forest structure exactly might not be appropriate in a rapidly changing climate, given the possibility of different disturbance regimes in the future.

Fire, drought, and bark beetle influence are all connected. The effects of one can exacerbate the effects of the other two. With longer droughts in the summer, water becomes a limiting resource, which affects the tree's ability to produce the chemicals which it uses to defend itself against insect infestation. The production of this resin is one of the first mechanisms that a tree will relinquish when resources are so limited. Bark beetle infestations increase, easily moving through large swaths of forest that has become dense from a century of

fire exclusion. While mortality from bark beetles is an important part of a natural system, if a forest is made more susceptible to infestation through water stress and high density, then the bark beetle populations no longer behave naturally (Christiansen et al. 1987). The increase in dead, dry biomass from widespread bark beetle-caused mortality creates conditions for a high severity fire.

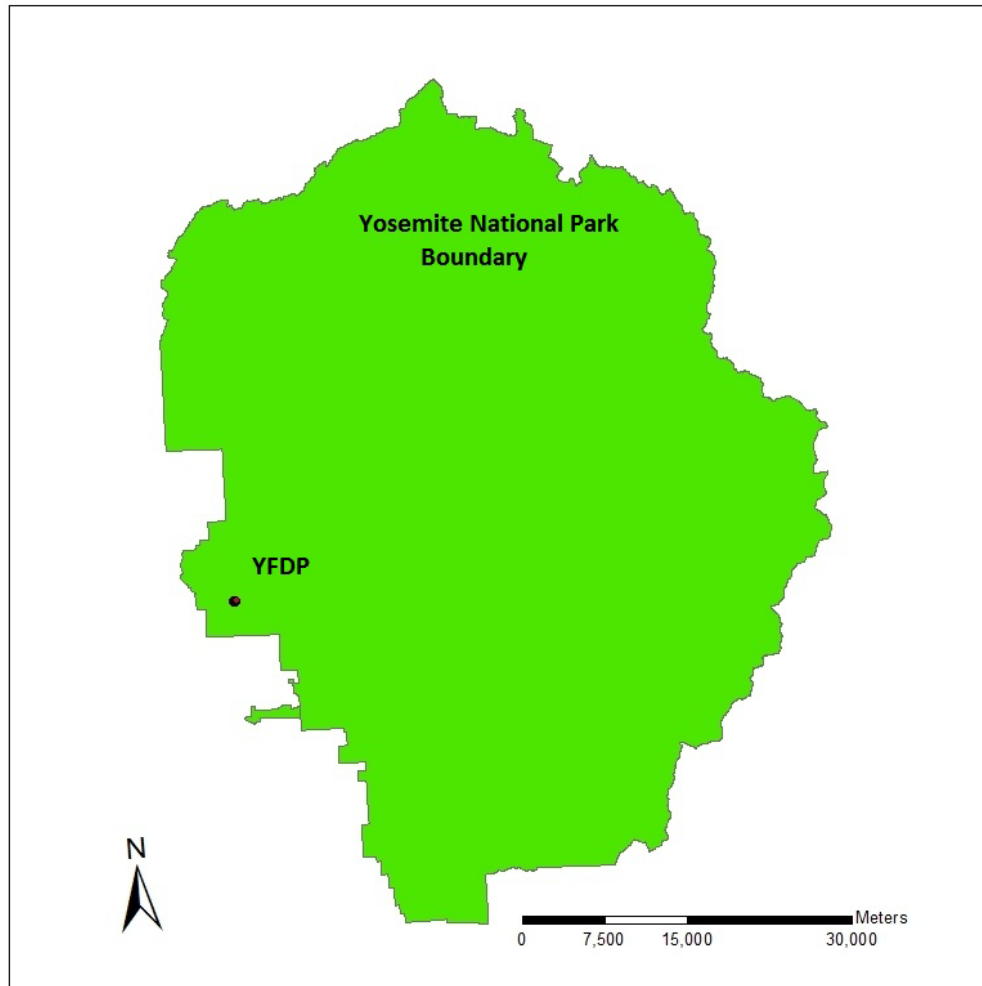
Methods

The study took place within the Yosemite Forest Dynamics Plot (YFDP), a 25 hectare, long-term structural dynamics plot that is currently being established in Yosemite National Park, California. It is one of five large scale forest dynamics plots in North America, researching the subtle dynamics of the recruitment and mortality of small trees (Moore and Lutz 2009). The average elevation of the site is 1869 meters (range of 1817 m to 1911 m). The weather cycles between warm, dry summers and cool, wet winters. The annual precipitation for the area is 1097 mm (PRISM 2009). The average slope was 20.5 degrees (range of 0-32.2 degrees) (Barth unpublished). The plant association type is sugar pine-white fir-incense cedar (*Pinus lambertiana*, *Abies concolor*, *Calocedrus decurrens*, respectively).

The plot was divided into 20x20 meter cells, oriented approximately to the four cardinal directions, using land surveying total stations. Sufficient line of sight was achieved by manually displacing obstructing branches, and releasing them after sighting. Tree data was taken on all live tree species, greater than 1 cm dbh on 10.2 hectares. Standing dead trees (snags) ≥ 10 cm dbh were also documented. Data including x-y coordinates, dbh, species, and relative vigor or decay class, were documented and the trees were subsequently tagged. Live trees were tagged by nailing stems greater than 3 cm dbh, and wiring stems 1-3 cm dbh for future measurements.

Total and per-hectare basal area and stem density for each species were calculated. Differences between 1899 and 2009 data were determined to develop a theoretical removal list. Three different silvicultural prescriptions were developed based on the range of the density of *A. concolor* estimated by Scholl and Taylor (in press). The mean density of the 1899 estimate was used as a goal for the maximum removal prescription (MaxP). The upper limit of the range of the density was used as a goal for the minimum removal prescription (MinP). A third prescription split the difference between these two removal rates (MedP). Trees were then selected at random to match the percent removals in each scenario. Tree lists were then analyzed in ESRI ArcGIS to produce actual (Figure 1) and theoretical (Figure 2, 3, and 4) stem maps. The three theoretical prescriptions focused on diameters greater than 10 cm. An upper diameter limit of 80 cm dbh was chosen because, above this diameter, current stocking levels of *A. concolor* in the YFDP do not differ greatly from Scholl and Taylor (in press) estimates of historic levels.

Figure 1. Map of Yosemite National Park Boundary and location of Yosemite Forest Dynamics Plot (YFDP).



For the MaxP theoretical prescription the CVTS (cubic volume including top and stump) was calculated using the white fir-specific equation (Cochran 1985 found in Bell and Dillworth 2007). Because no height measurements of live trees were made during the study, the heights used in the volume calculations were taken from *A. concolor* standing dead trees (snags) with decay class of 1. Snags of this decay class still have an intact leader, and this approximates the height of live trees of similar diameter. CVTS volume was used for further calculations because the calculated CV4 (cubic volume to a 4-inch diameter top) and CV6 (cubic volume to a 6-inch diameter top) values began to surpass the CVTS values around 36cm dbh, suggesting a decrease in accuracy. The CVTS of the theoretically removed trees was used to estimate tons/ha using conversions for softwoods found in Haynes (1990). Numbers were then converted to metric units.

Cost estimates obtained from regional logging industry corporations would be the most accurate (Keegan et al 2002) however, such information is proprietary. Of the four approaches to cost analysis outlined by Rummer (2008), I chose the expert opinion approach for its simplicity and ability to provide current numbers. However, Rummer (2008) also cautions against taking anecdotal, site-specific cost figures and applying them to a different region. To minimize the effect of regional differences, cost references were obtained that apply to U.S. West dry forests; some from studies in the Sierra mixed-conifer zone.

A cost estimate was developed for each of the treatment scenarios. Costs include harvest and transportation of merchantable trees (≥ 10 cm dbh), and administrative overhead. Costs were not estimated for trees less than 10cm dbh. Revenue of \$100/MBF was assumed based on the volatility of the market. Simple harvest cost equations for ground-based yarding and cable-based yarding methods were used from McDonald (2010):

\$41*ton for ground-bases systems

\$115/ton for cable-based systems

Transportation cost equation was used from Ettl (2009), in US dollars and short tons:

$(2.14 * \text{ton}) + (0.045 * \text{miles} * 0.5 \text{ton})$

An additional 40% fuel charge was assumed for transportation costs. Administrative costs were assumed to be 10% of total costs (Rummer 2008).

Results

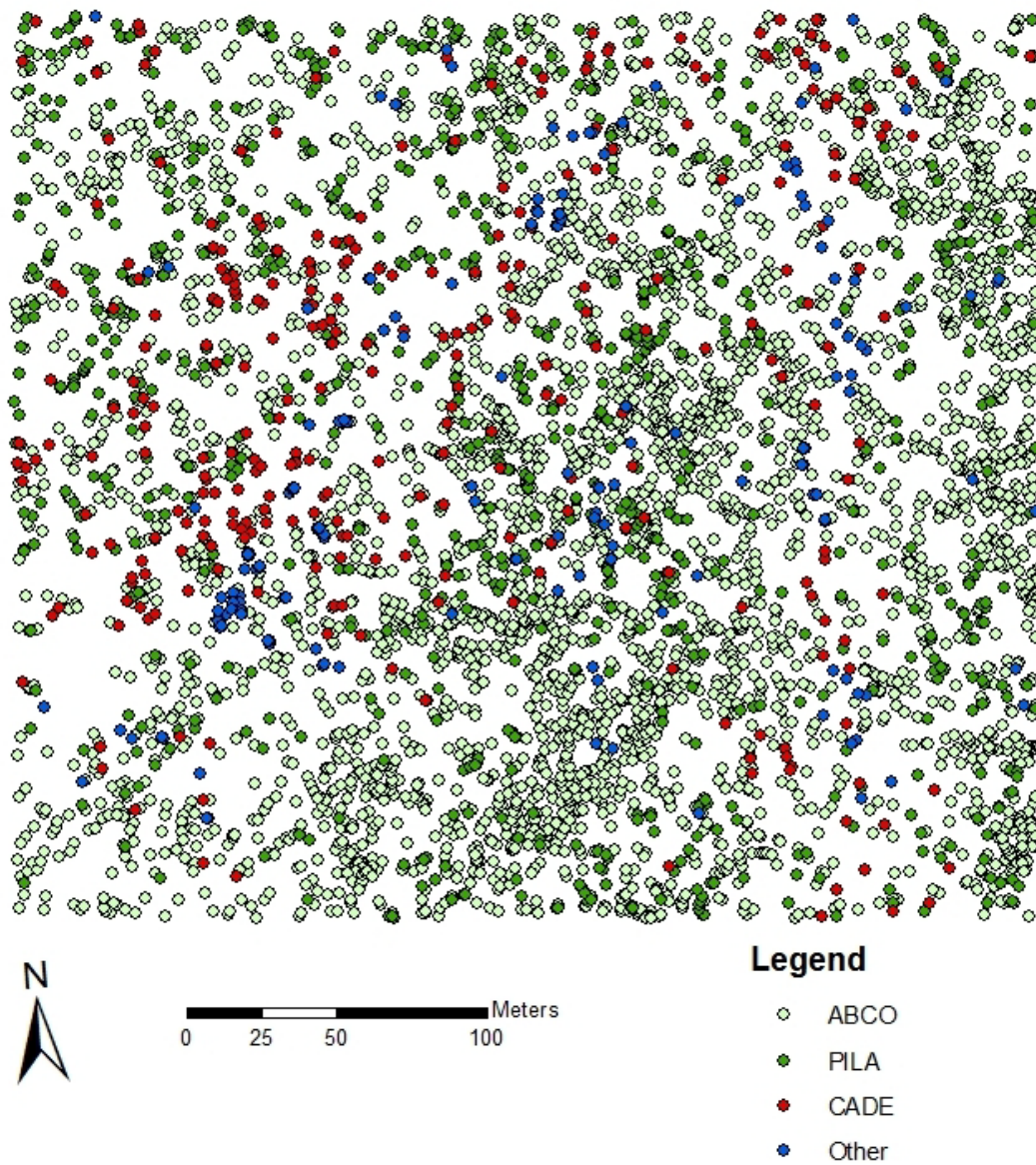
For live trees ≥ 10 cm dbh in 2009 total tree density was 449 stems/ha, and total basal area was 65.8 m²/ha (Table 1, Figure 1). *Abies concolor* was the most abundant species, 329 stems/ha, but *Pinus lambertiana* had the highest basal area, 31.7 m²/ha. In terms of stem density, ABCO represents 73% of the live trees. 2009 conditions contain on average 86% more *A. concolor* stems than 1899 in the 10-80 cm diameter classes on average.

ABCO, CADE, and PILA together make up 99% of the total basal area of the plot. The size class distributions for ABCO, PILA, and CADE were a reverse-j curve: stems-per-hectare decreased as diameter increased. Standing dead trees (snags) occurred at 89.2 stems/ha with an average basal area of 18.95 m²/ha.

Table 1. Mean density (stems/ha) and basal area (m²/ha) of all live trees by diameter class (cm) in 10.2 hectares of the Yosemite Forest Dynamics Plot 2009. Species acronyms are ABCO (*Abies concolor*), CADE (*Calocedrus decurrens*), and PILA (*Pinus lambertiana*). Other species include *Abies magnifica*, *Cornus nutallii*, *Pinus ponderosa*, *Quercus kelloggii*, *Prunus emarginata*, *Corylus cornuta* var. *californica*, *Salix* spp., *Rhamnus californica*.

DBH Class	ABCO		PILA		CADE		Other		Total	
	Density	BA	Density	BA	Density	BA	Density	BA	Density	BA
1-10	573.0	1.2	72.7	0.1	26.3	0.1	109.6	0.1	781.7	1.6
10-20	182.1	2.9	19.1	0.3	13.2	0.2	14.8	0.2	229.2	3.7
20-30	69.5	3.3	9.7	0.5	5.1	0.2	1.9	0.1	86.2	4.1
30-40	28.4	2.6	6.9	0.7	2.6	0.2	0.1	0.0	38.0	3.5
40-50	16.6	2.6	3.7	0.6	1.4	0.2	0.2	0.0	21.9	3.4
50-60	9.3	2.2	3.1	0.7	1.8	0.4	0.0	0.0	14.2	3.4
60-70	6.0	2.0	3.7	1.2	0.6	0.2	0.1	0.0	10.4	3.5
70-80	6.4	2.7	3.8	1.7	1.0	0.4	0.0	0.0	11.2	4.9
80-90	2.9	1.7	3.7	2.1	0.7	0.4	0.0	0.0	7.4	4.2
90-100	2.5	1.8	3.6	2.6	0.9	0.6	0.0	0.0	7.1	5.0
100-110	2.8	2.4	3.4	3.0	0.9	0.8	0.0	0.0	7.2	6.2
110-120	1.3	1.4	3.2	3.4	0.3	0.3	0.0	0.0	4.8	5.1
120-130	0.4	0.5	2.8	3.5	0.6	0.7	0.0	0.0	3.8	4.7
130-140	0.5	0.7	2.1	2.8	0.0	0.0	0.0	0.0	2.5	3.5
140-150	0.3	0.5	1.0	1.6	0.4	0.6	0.0	0.0	1.7	2.7
150-160	0.0	0.0	1.8	3.5	0.1	0.2	0.0	0.0	1.9	3.7
160-170	0.0	0.0	0.7	1.5	0.3	0.6	0.0	0.0	1.0	2.1
170-180	0.1	0.2	0.6	1.4	0.0	0.0	0.0	0.0	0.7	1.6
180-190	0.0	0.0	0.2	0.5	0.0	0.0	0.0	0.0	0.2	0.5
190-200	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200-210	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.0	0.1	0.3
Total	902.2	28.8	146.1	31.8	56.1	6.3	126.7	0.5	1231.0	67.4

Figure 1. A stem map of live trees ≥ 10 cm dbh in the YFDP 2009.



Removing a random 90% of *Abies concolor* between 10 and 80 cm dbh (the MaxP theoretical prescription) results in a stand basal area of 49.5 m²/ha. The percent of *A. concolor* basal area (m²/ha) was reduced from 43% to 11.3% of the stand basal area. The removed volume in this prescription was 164 m³/ha, with an estimated weight of 81.6 metric tons/ha. The cost of this prescription was estimated to be \$12077/ha if a cable yarding-based harvesting system is used. The possible gross revenue was estimated to be \$6964/ha. This results in a net cost of \$5113/ha. Using a ground-based harvesting system would result in an overall cost of \$4755/ha and a net revenue of \$2209/ha. The results of all three theoretical prescriptions can be found in Tables 3-5.

Table 2. Comparison of major tree species density (stems/ha) by diameter class (cm) between YFDP 2009 and 1899 reconstruction by Scholl and Taylor (in press). Species acronyms are CADE (*Calocedrus decurrens*), PILA (*Pinus lambertiana*), and ABCO (*Abies concolor*).

DBH Class	CADE		PILA		ABCO	
	1899*	2009	1899*	2009	1899	2009
one-10	N/A	26	N/A	73	N/A	573
ten-twenty	16	13	7	18	11	182
20-30	6	5	6	10	5	70
30-40	6	3	3	7	3	28
40-50	4	1	3	4	3	17
50-60	4	2	2	3	2	9
60-70	4	1	1	4	1	6
70-80	4	1	1	4	1	6
80-90	4	1	1	4	1	3
90+	10	3	11	20	1	7

Table 3. Resulting stand characteristics after theoretical removal of live ABCO (*Abies concolor*) stems 10-80cm dbh.

Prescription	Removal of ABCO	Stems/ha removed	BA/ha removed	Total Stand BA/ha after treatment	Proportion of ABCO density to stand
MaxP	90%	286	16.3	49.5	9.6%
MedP	60%	191	10.9	54.9	30.8%
MinP	30%	96	5.3	60.5	51.9%

Figure 2. A stem map showing live trees $\geq 10\text{cm dbh}$ in the YFDP 2009 after the MinP theoretical prescription.

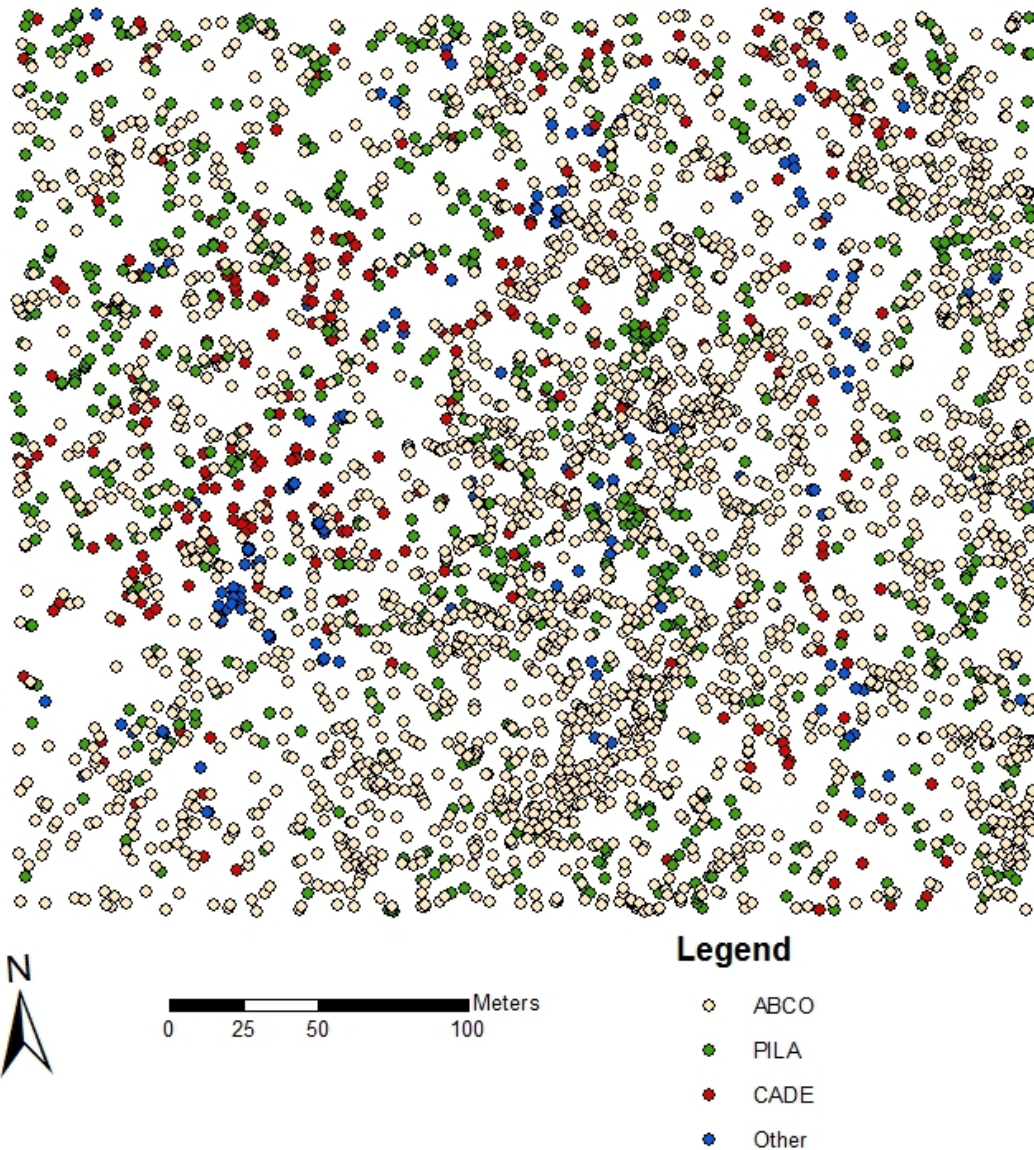


Table 4. Merchantable biomass removed (metric tons/ha) and resulting costs, revenue, and.... net gain (\$/ha) using a ground-based yarding method.

Prescription	Tons Removed	Cost				Revenue	Net
		Harvest	Transportation	Administrative	Total		
MinP	26.27	977	404	10%	1519	2242	723
MedP	54.45	2025	837	10%	3149	4647	1498
MaxP	81.61	3035	1255	10%	4719	6964	2245

Figure 3. A stem map showing live trees $\geq 10\text{cm dbh}$ in the YFDP 2009 after the MedP theoretical prescription

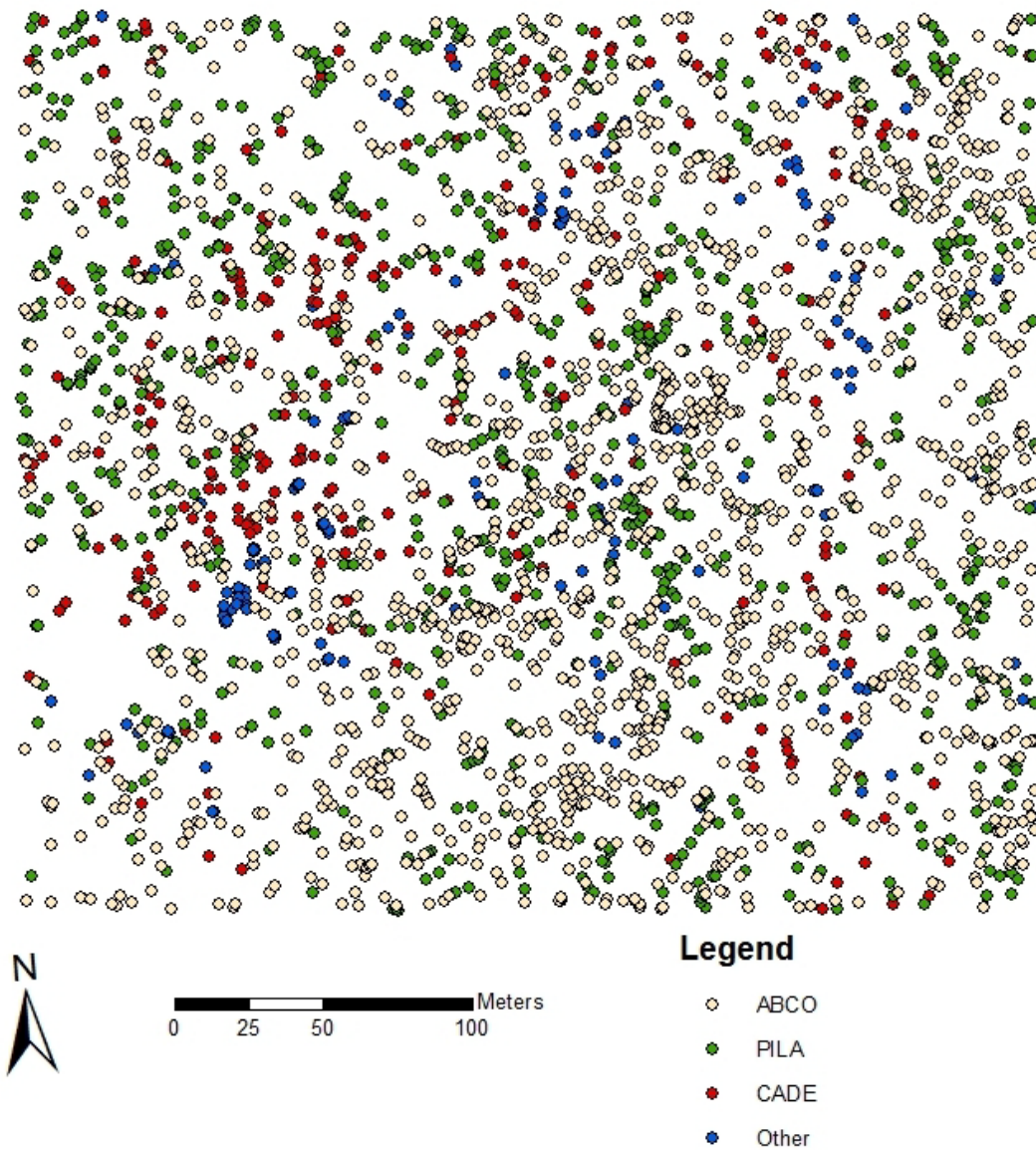
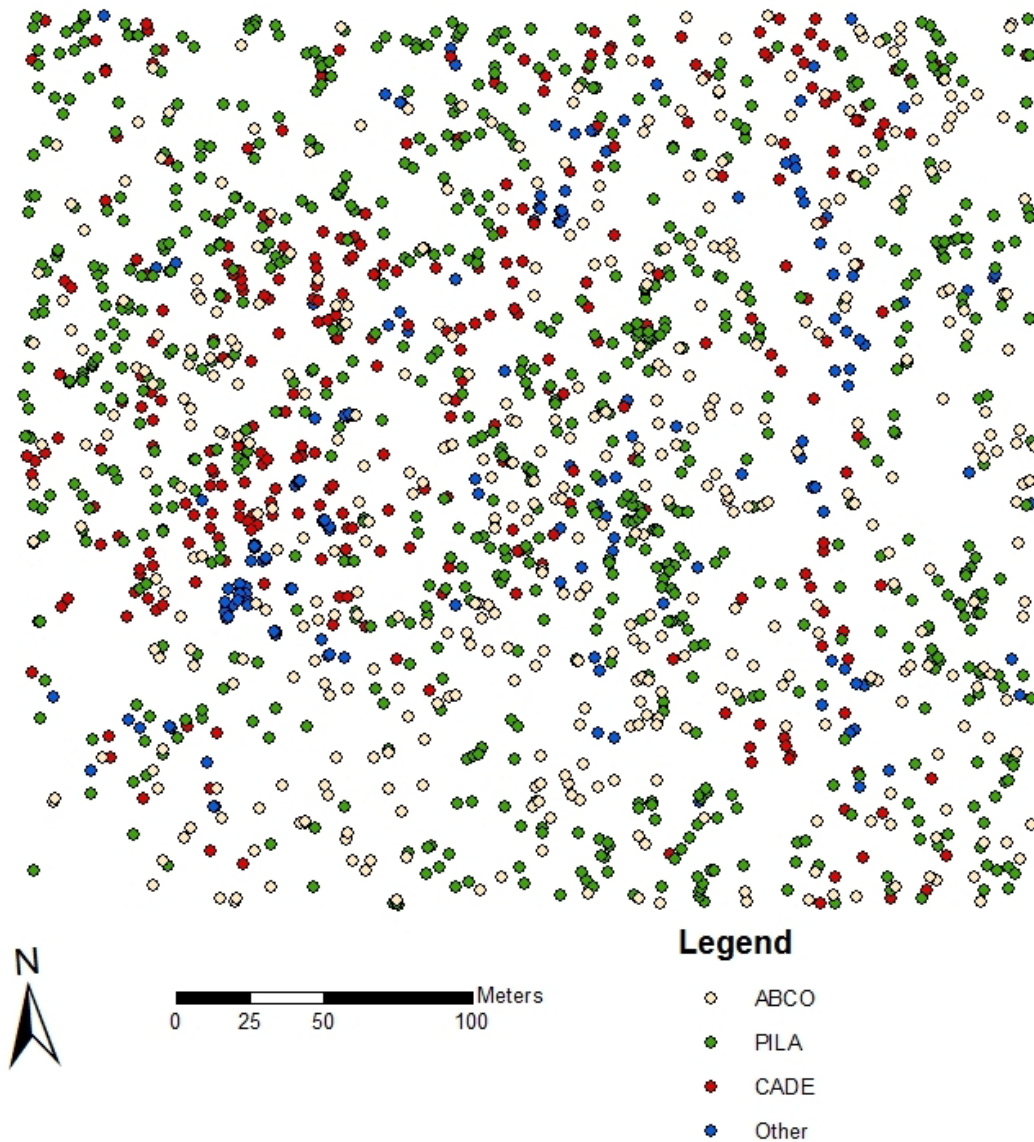


Table 5. Merchantable biomass removed (metric tons/ha) and resulting costs, revenue, and net loss using a cable-based yarding method.

Prescription	Tons Removed	Cost				Revenue	Net
		Harvest	Transportation	Administrative	Total		
MinP	26.27	2740	404	10%	3458	2242	-1217
MedP	54.45	5680	837	10%	7170	4647	-2523
MaxP	81.61	8513	1255	10%	10745	6964	-3781

Figure 4. A stem map showing live trees $\geq 10\text{cm}$ dbh in the YFDP 2009 after the MaxP theoretical prescription.



Discussion

Barriers to Restoration

Implementing fuels reduction treatments on the landscape level faces barriers; the largest of which is the cost (Friederici 2006) which can be up to \$2470/ha (Rummer et al 2005). To mitigate a substantial amount this cost, there are potential sources of revenue including the sale of merchantable trees. An investment of \$550 per acre (\$1359/ha) would see returns in the form of saved fire suppression costs (Snider et al 2003). Ince et al (2008) likewise

recommend subsidies for thinning programs. There is also an opportunity to generate revenue from the sale of merchantable timber.

The conundrum of whether to dispose of or utilize biomass from mechanical fuels reduction treatments is a significant barrier (Rummer et al 2005, Barbour et al 2008). If the distance to market is much farther than a landfill, then it is more economical to dispose of the biomass rather than turning it into energy through cogeneration combustion (burning biomass with coal or other fuel for energy production) or biofuel production (such as methanol, or fast pyrolysis). Polagye et al (2007) concluded that using biomass for energy is more economical than disposal or in situ burning, within a given distance to market. In the context of the YFDP, cogeneration plants are as close as Stockton, Ca, which is 120 miles (193 km) from Yosemite Valley. It would therefore be economical to transport and sell the clean and dirty chips from harvested stems less than 10cm dbh and tops and branches to a processing facility in Stockton.

The most important metric for the ecological restoration of our Nation's Forests is not diameter at breast height. With millions of hectares in need of restoration (Franklin and Agee 2003) constraints to management should be entirely ecologically-based. A successful fuels reduction prescription should be adaptive, flexible, and without a ridged upper diameter limit (North et al 2007). However, because of the ecological and social importance of big trees, there must be some upper diameter limit in order to keep the largest trees.

Prescriptions

Scholl and Taylor (in press) estimated total stand basal area in similar forest types to be 29.9 m²/ha in 1899. When the standard deviation (19.6) is considered, the MaxP scenario fits this estimation with a stand basal area of 49.5m²/ha. *A. concolor* basal area per hectare was estimated to be 1.8 with a standard deviation of 3.7 in 1899. The MaxP scenario resulted in a basal area of 11.3 m²/ha for *A. concolor*. This suggests that even with a randomly selected 90% of stems 10-80cm dbh, there is possibly a greater retention of *A. concolor* in these prescriptions than that was historically present. However, if Scholl and Taylor's (in press) 1899 estimate of the upper limit of the range of basal area for *A. concolor* (19 m²/ha) is the appropriate figure for the historic conditions of this particular stand, then the MinP or MedP prescriptions would more closely achieve these results with an average basal area of *A. concolor* of 22.3 m²/ha and 16.7 m²/ha, respectively.

Assuming a price of \$100/MBF, the MaxP theoretical scenario generated a revenue of \$2245/ha with the ground-based system, and a cost of \$3781/ha with the cable based system. The cable based system cost almost three times more per ton than the ground-based system. This coupled with the large calculated weight of 81 metric tons/ha led to the broad range in net

results between the two harvest methods. The volume and weight may have been overestimated because the calculation included the top and stump in the volume (CVTS).

Each theoretical prescription resulted in a visually different forest structure. However they all maintained a generally heterogeneous vertical pattern with clumps and gaps. This was in part due to the retention of all species other than *A. concolor*. The leave trees in this treatment are spatially aggregated. The random selection method also contributed to the maintenance of patchy pattern.

A benefit of a prescription that is based on diameter distribution and not an upper diameter limit or traditional classification (e.g. thin from below, thin from above, etc), or a bottom line stand basal area is that it is an ecosystem approach. The theoretical prescriptions explored in this study were focused on changing the stand's structure and species composition to mimic historic conditions. These prescriptions were not concerned with individual tree structure (i.e. whether or not each removed tree was perceived as "big"). Rather, the focus was on the broader stand structure. These prescriptions do not take a landscape level approach either. These prescriptions are only applicable in stands with similar species composition, structure, and high density of *A. concolor* (i.e. similar ecosystems).

While the density of *Pinus lambertiana* and *Calocedrus decurrens* in the Yosemite Forest Dynamics Plot closely matches the 1899 reconstruction from Scholl and Taylor (in press) (Table 2), it is evident that the current density of *Abies concolor* is nearly 90% higher throughout diameters 10-80 cm. Table 2 shows the difference in density of major species between an 1899 reconstruction and current conditions. The difference in density becomes less above the 70-80 cm diameter class. On average, *A. concolor* is present in numbers more than 8 times greater than 1899 conditions between 10 and 80 cm dbh. *A. concolor* represents 43% of total basal area of the plot, compared to 12% in the 1899 reconstruction. The majority of *A. concolor* stems occur in the small diameter classes, therefore representing a proportionally small basal area compared to *P. lambertiana*. This suggests that a silvicultural prescription focusing on *A. concolor* would be effective in meeting structural restoration objectives.

Forest inventory was compared to Scholl and Taylor (in press) 1899 reconstructions of Sierra mixed-conifer stand structure in the vicinity of the YFDP plot. Data from the white fir-sugar pine plant association forest type were chosen for comparison because the YFDP had similar species composition. The 1899 reconstruction did not estimate any stems below 10 cm dbh because any trees that died that young would be completely decomposed by the time of the 2001 study. For the same reason, the number of small diameter trees (10-20 cm dbh) may have been underestimated. However, the Scholl and Taylor study also included a 1911 timber survey in the same area with consistent basal area findings.

While the 1899 estimate may underestimate small diameter trees due in part the short lifespan and decayspan of such small trees, the basal area per hectare may be a more reliable figure because of large diameter tree's greater influence of the average basal area per hectare. Their estimates are more accurate for larger trees. Therefore, the difference between the 1899 estimates and 2009 measurements are a good approximation for developing a silvicultural prescription.

Knapp et al (2004) found that fire exclusion has led to a greater density and proliferation of *Abies concolor*. This density of *A. concolor* has been found in other studies as well. Ansley and Battles (1998) measured 420 stems/ha of this species on a 4-ha plot in an old-growth mixed-conifer forest in northern Sierra Nevada. This high stem density *A. concolor* dominates much of California's mixed-conifer forests (North et al. 2006). The mixed-conifer forest type composes 10% of the vegetative area of the Sierra Nevada ecosystem in California (McKelvey et al. 1996).

Unprecedented, high-severity fire has become a greater threat to our nation's old forests than the threat of logging (Healy et al. 2008). Dry, mixed-conifer forests with big old trees and high densities of fire-prone, small diameter stems are in need of active management; fire cannot be excluded from these ecosystems forever. Retaining large trees is a well documented component of promoting a stand's fire resilience (McKelvey et al. 1996; Agee and Skinner 2005).

There are difficulties in implementing a prescription that removed a random set of stems. Stands in need of treatment rarely have inventories as detailed as the YFDP. Generating a random list of trees within given parameters is therefore impossible. If an inventory does exist for a stand that will be treated with mechanical thinning, it would still be difficult to translate a removal list to on-the-ground operations. Prescriptions therefore need to be flexible and adaptive.

Ecological

While it is inappropriate to implement a generic prescription without considering site-to-site variability (Franklin and Agee 2003) there are some well-researched guiding principles that are relevant to any fuel reduction treatment. Removal of small diameter trees in a historically fire-suppressed forest results in a much higher survival of basal area after a fire (Agee and Skinner 2005). The overall structural pattern should be patchy and non-uniform to mimic historic patterns (Hessburg et al 2005, McKelvey et al. 1996).

To reduce the risk of a high severity, stand-replacement fire, Agee and Skinner (2005) identifies three sources of fuel that need to be reduced: (1) surface fuels, (2) crown density, and (3) ladder fuels. As guiding prescription, the Structured Ecological Thin from Sprugel et al.

(2009) was used. This model paralleled the recommendation of Hessburg et al (2005) that a fuels reduction thin restore the stand to a more natural structure, not only reduce the amount of fuels. On this site, these goals can be achieved by focusing on removing large percentages of white fir (*Abies concolor*), mainly in the smaller diameter classes.

The focus on *A. concolor* is also important on the tree-level scale. *A. concolor* are not as fire resistant as *Pinus lambertiana* and they are not as drought resistant as *Calocedrus decurrens*. While *A. concolor* have historically existed in a fire-adapted environment, they have done so due in part to the patchy, mosaic pattern of fire on the landscape. With increased densities of the fire-vulnerable *A. concolor*, comes an increased hazard of a stand-replacement fire.

Land managers must be current with the latest research as well as the historic structures and functions of the ecosystem in which they are working. While the benefits mechanical and prescribed burn treatments are well documented (van Wagten 2004, Agee and Skinner 2005, Stephens and Moghaddas 2005, North et al. 2007) science and social perspectives are constantly changing. It is therefore important to stay up-to-date on the latest fuel treatment science. This is especially important in the context of climate change. Warmer climates in Sierra Nevada ecosystems will mean less snowpack, earlier runoff, and longer summer droughts (Hayhoe et al 2004). The effects of less precipitation are more pronounced in lower montane forests. Above 1500 m elevation, the moisture of fuels becomes increasingly critical in the extent of the area burned by fire (Miller and Urban 1999). The results from these studies affect how land managers should proceed. The retention of drought and fire resistant species becomes all the more important.

Hardwood species (*Quercus kelloggii*, *Cornus nutallii*, *Prunus emarginata*, *Corylus cornuta* var. *californica*, *Salix* spp., and *Rhamnus californica*) should be retained for their biological diversity and unique ecological functions. Because these species occur at low densities in the plot, they pose a lesser risk of acting as a ladder fuel or carrying a crown fire than does *Abies concolor*. *C. nutallii* is even less of a hazard because it occurs in wetter areas. To reduce these risks further, Schmidt and Wakimoto (1988) suggest a 3 meter buffer around the crown of these ecologically valuable trees that pose a ladder fuel hazard. That is, unless an equally ecologically valuable tree falls within that buffer. By preserving these infrequent species during a mechanical thinning, their relative abundance as a percent of the stand's basal area can be increased. In the MaxP theoretical treatment, 90% of the *Abies concolor* stems between 10 and 80cm dbh were removed. This increased the relative basal area of rare, "other" species (see Table 1) from 0.7% to 1.0% of total stand basal area.

Quercus kelloggii is an abundant acorn producer which is an important food source. It is able to sprout growth after it has been burned over by fire, making it a potential biological

legacy after disturbance (Franklin et al. 2007). *Q. kelloggii* also contributes to the aesthetic of the stand. Its leaves have beautiful “deeply divided, bristle-tipped lobes” (Kershner et al. 2008) that resemble fire. In the autumn the leaves turn brilliant red-orange, adding to this effect. This tree is sensitive to drought. If climate projections are correct for this area (Hayhoe et al. 2004), then the preservation and promotion of *Q. kelloggii* will become more difficult. *Cornus nutallii* provides flowers with showy bracts that can attract invertebrate pollinators. This tree booms twice a year: in early spring-summer and again in late summer-autumn (Kershner et al. 2008). Curiously, this pattern seems to mimic the seasonality of a natural fire regime as delineated by van Wagtenonk and Lutz (2007). *Prunus emarginata* is common in burned-over lands and therefore could serve as a biological legacy after disturbance (Franklin et al. 2007). This tree can also mitigate erosion with roots spreading up to 15 meters (50 feet) (Kershner et al. 2008). This is especially important after a disturbance.

Mechanical treatments can negatively impact soil by altering soil physical, chemical, and biological properties (Page-Dumroese et al. 2010). Steps should be taken to minimize the area of disturbed soil. The goal of fuels reduction treatments is restoration; the type of harvesting method should reflect this. By working in corridors and forwarding logs with a skyline, cable yarder or small tractor forwarder, the area of affected soil can be minimized. Ideally, a skyline cable system would be used as it would disturb the soil less than a tractor forwarder that would have to make multiple passes over the same corridor. Helicopter logging would disturb the soil the least, but the high cost of this method makes it uneconomical for thinning prescriptions (Han et al. 2004). Operations during wet seasons can cause soil mixing and re-direct water flow off the site (Page-Dumroese et al. 2010). Therefore, the seasonal timing of mechanical operations should be factored in to a site-specific plan.

The seasonal timing of prescribed burns also is important (van Wagtenonk and Lutz 2007). Burning during a season that did not historically have wildfire can negatively impact seed germination or herbaceous plants and breeding of nesting animals (van Wagtenonk and Lutz 2007 and references therein). When coupled with the seasonal variability of harvest impacts on soil, the window of operation becomes smaller.

Fire regimes must be restored with fire (van Wagtenonk 2004, Agee and Skinner 2005). A mechanical treatment alone is inadequate to restore the forest to a functional low-severity fire ecosystem. Because areas adjacent to a mechanical treatment may still be fire-suppressed, it could take a few years for a fire to be naturally ignited in the treated stand. During this time trees have an opportunity to germinate and grow, replacing the removed trees with comparable densities. It is therefore desirable to conduct a prescribed burn immediately following a mechanical thinning in a fuels reduction treatment.

Across the US West, old forests are experiencing an increase in mortality (van Mantgem et al. 2009). While fire exclusion may not be the root problem of this increase, it does interact with other contributing factors. Van Mantgem et al. (2009) conclude that the dominant driver of this increased mortality is average regional temperatures which lessen snowpack and increase summer drought severity and duration. This affects hydrologic cycles, decreasing the availability of water which is a limiting resource in dry forests. This lack of water coupled with higher competition from increased density of small diameter trees that were historically controlled by fire could be contributing to the observed increase in tree mortality.

Snags are an important consideration in any silvicultural operation. The stochastic nature of a snag's mechanical breakdown makes them a safety hazard for workers operating equipment underneath them. It is necessary to work around these standing dead trees and avoid felling trees into them. This is another reason for keeping prescriptions flexible. Snags also should be preserved for their ecological functions (Franklin et al. 2002). Standing dead trees provide habitat for organisms that provide further ecological functions. Even in the event of a stand-replacement fire, large snags are not wholly consumed. They therefore serve a "lifeboating" function that facilitates the regeneration of the ecosystem (Franklin et al. 2007 and references therein).

If maximizing a thinning prescription's effectiveness via a reduction in torching hazard is a main goal, then Barbour et al. (2008) suggests that a considerable amount of merchantable trees would have to be removed. Removing these larger, merchantable trees would reduce the fire hazard of a forest by reducing the stem density which decreases the potential for a crown fire (Agee and Skinner 2005). The purpose of silvicultural mitigations to forest fire hazard is ecological restoration; studies that analyze the economics of such operations should incorporate ecological arguments for the removal of trees.

Economic

To maximize the ability to restore forests on the landscape-level, "...large-scale fuels treatments will have to be an economically self-sustaining enterprise, supported largely from the sale of forest products" (McKelvey et al. 1996). In practice, mechanical fuels reduction treatments do not create tangible net revenue (Hartsough 2003; Han et al. 2004; Polagye et al. 2006). However, climate, timber market prices, biofuels technology, and public perception of the environment are all experiencing changes that affect the way forests will be managed in the future (Gustafson and Loehle 2008; Rummer 2008). This includes the methods and objectives of forest thinning prescriptions. Whatever changes may occur, old, structurally heterogeneous forests are a vital part of our environment and conservations of such forests should be a main goal of land management.

Because of variability in environmental conditions, methodology, and market prices, the cost of thinning operations can have a broad range of 86 - 2470\$/ha (Rummer et al. 2005). Relative environmental conditions such as low stem density, steep slopes, and the need to install road and culverts will increase the cost of the operation (Keegan et al. 2002; Han et al. 2004; Rummer 2008). Prescribed burning should follow any mechanical treatment so these costs must be considered as well. Agee and Skinner (2005) recommend multiple follow-up burns because initial burns can increase the growth of young vegetation. These follow-up burns could increase overall costs by up to \$300/ha (McDonald 2010).

Assuming a market price for biomass as dirty chips to be \$18/ton (Barbour et al. 2008), the cost to removed sub-merchantable trees would have to be kept low to make a fuels reduction treatment economical. This could be achieved by treating larger contiguous areas of land within a distance of less than 400km to a co-fire facility (Polagye et al. 2007).

Manual removal is likely needed for some trees to minimize compaction of soil, and the precise identification of the appropriate removal tree. This could increase costs, but provide more jobs at the same time. Whole tree harvest is most effective in preventing surface fuels (Agee and Skinner 2005) compared to other harvesting methods. Han et al. (2004) found that this method removes a significant volume of fuels, yet does cost more than a tree-length or cut-to-length harvesting method. For this prescription, I assume a whole tree harvest with cable yarding system costs \$110-120/ton (McDonald 2010).

Considering economies of scale, as the volume and area of forest treated increases, costs decrease (Rummer 2008). The cost estimates in this study do not take this into account. However, the resulting cost estimates from this study were close to the published cost estimates of fuels reduction thinning of \$86-2470/ha (Rummer et al. 2005). This suggests that, while simple, this cost model is useful in comparing general trends between harvested volumes and methods, if not absolute costs.

Similarly, as the diameter of harvested trees increase, costs of removal decrease (Keegan et al. 2002; Han et al. 2004). In other words, larger trees generate more revenue. This is an argument used by contractors working on thinning prescriptions to remove commercial-sized trees. This leads to social backlash if revenue is the only basis for removing these trees. It is therefore necessary to justify the removal of large trees on the basis of ecological reasoning, not just economic.

Social

While prescribed fire was being more widely accepted in the 1970s, regulations began to be adopted that were designed to protect valuable elements of the environment from the negative impacts of humans (Arno and Allison-Brunnell 2002). Ironically, these lands were

already affected and possibly too far altered to be self-preserving. One of the main objectives of the management of our nation's forests is the preservation of biological diversity; the way to do this is with an ecosystem-level approach (Franklin 1993). Trees provide the primary above-ground structure of the forest ecosystem. By focusing management practices on silvicultural prescriptions, the greatest amount of influence can be achieved. While mechanical thinning treatments are not appropriate in all forest ecosystems, fuels reduction prescriptions should be more widely tested and applied.

Using machinery and fire to alter our nation's forests is a contentious issue (Noss et al 2006). A fuels reduction prescription should therefore explicitly address the social impacts of implementing the prescription. Environmental organizations such as the Sierra Club have barred many fuels reduction operations and other active management projects. Through blanket court appeals, an arbitrary rhetoric of "no tree over 21 inches (53 cm) DBH removed" has been imposed on the forest service (McDonald 2010). While the public should have a say in what happens to our nation's forests, it is important that our decisions are ultimately based on empirical, ecologically-grounded science. A. concolor in some stands is occurring in densities above 21" (53 cm) dbh that are clearly above characteristic conditions (Table 2). Opposition to fuels reduction treatments must be explicitly addressed in the actual plan or prescription. It should be up to the land managers to provide those with opposing opinions with the appropriate publications and research that outline why thinning prescriptions are necessary in some forest stands.

The environmentalist community strongly opposes the removal of trees greater than 21 inches (53 cm) on public lands (McDonald 2010). While big old trees must be preserved for their fire resilience and other ecological functions (Agee and Skinner 2005; Franklin et al 2007), there are more important properties of old trees than simply the diameter at breast height (van Pelt 2008). Individual tree structure is an important part of the tree's ecological function. The more variegated and unique the structure, the more attractive it is to nesting wildlife. An old tree growing on marginal land (such a steep slope or poor soil) will not be as big as a tree of the same age growing in a more productive area. The tree growing in the marginal area may be more vital to the ecosystem because it has adapted to these conditions and fills a unique niche.

Fuels reduction prescriptions do address the need to minimize the quantifiable negative impacts of a prescribed burn. Specifically, plans are coordinated to minimize the impact on air quality from smoke (USDA 2007). However, as more lands are potentially treated with mechanical thinning under the Healthy Forest Initiative the public may become more outspoken about removal operations in old forests. It is the intense, high severity wildfires that most negatively affect society and clash with their values (McKelvey et al. 1996).

Communicating the idea that we need to keep our options open in restoring an ecologically functional fire regime to our nation's forests is an important first step.

Conclusion

Dry, mixed-conifer forests with big old trees and high densities of fire-prone, small diameter stems are in need of active management; fire cannot be excluded from these ecosystems forever. I have provided ecological, economic, and social arguments to develop fuels reduction plans that remove larger diameters of *Abies concolor* than are currently being practiced. By comparing current stocking levels to historic reconstructions (Taylor and Scholl in press), it is evident that *Abies concolor* is now present in higher densities and larger sizes than 19th century conditions. Sierra mixed-conifer forests that contain unnaturally high densities of *A. concolor* must be thinned in order to restore the structure to pre-suppression era pattern and facilitate historic fire regimes. In the case of the Yosemite Forest Dynamics Plot and much of California's forests, a significant reduction in stem density can be accomplished by focusing on removal of *A. concolor* while leaving the fire and drought resistant sugar pine (*Pinus lambertiana*) and incense cedar (*Calocedrus decurrens*) species. Arbitrary, species-irrelevant diameter limits are a barrier to achieving forest conditions that include a historic, ecologically functional, fire regime. Mechanical thinning alone is inadequate to treat the large tracts of land that are in need of restoration (van Wagtenonk and Lutz 2007). However, if it is possible to create revenue by removing a portion of the trees conventionally considered big—trees that may not have existed under a natural fire regime—then the ability to restore more forests is greater. The point is to increase the options land managers have for restoring an ecologically functional fire regime to Sierra Nevada mixed-conifer forests. If we wish to reduce unprecedented fire, we must do unprecedented things.

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