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Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios

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Forests are viewed as a potential sink for carbon (C) that might otherwise contribute to climate change. It is unclear, however, how to manage forests with frequent fire regimes to maximize C storage while reducing C emissions from prescribed burns or wildfire. We modeled the effects of eight different fuel treatments on tree-based C storage and release over a century, with and without wildfire. Model runs show that, after a century of growth without wildfire, the control stored the most C. However, when wildfire was included in the model, the control had the largest total C emission and largest reduction in live-tree-based C stocks. In model runs including wildfire, the final amount of tree-based C sequestered was most affected by the stand structure initially produced by the different fuel treatments. In wildfire-prone forests, tree-based C stocks were best protected by fuel treatments that produced a low-density stand structure dominated by large, fire-resistant pines.

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Global awareness of human effects on climate has increased in the past two decades and has led to international and regional, political, and economic efforts to reduce or offset greenhouse-gas emissions. Typically, offsets are achieved through afforestation and reforestation (Schulze *et al.* 2000; IPCC 2006: CCAR 2007) and require landowners to establish a carbon (C) baseline to quantify the amount of C stored on a given unit of forest land (IPCC 2006: CCAR 2007). As trees grow, C is sequestered, and these additional tons of C can be used to offset emissions in other sectors. In fire-prone forests, however, tree-based C storage may lead to large releases of C if trees are killed and partially consumed by a high-severity fire (Breshears and Allen 2002; Hurtt *et al.* 2002; Kashian *et al.* 2006; Hurteau *et al.* 2008).

Beginning in the mid-1900s, US forested lands became a net sink for CO_2, as a result of forest regrowth and fire suppression (Hurtt *et al.* 2002). Fire suppression has increased forest density and stand-replacement fire risk in forests that were historically characterized by frequent, low-severity fire regimes (McKelvey and Busse 1996). Commensurate with these changes has been a shift in climate, correlated with a longer wildfire "season" and an increase in large fire (> 9400 ha) frequency (Westerling *et al.* 2006). Catastrophic wildfire presents a risk to forest C storage (Breshears and Allen 2002).

In fire-prone forests of the western US, there are three common management practices for reducing forest biomass and the risk of catastrophic fire: prescribed fire, mechanical thinning, and both treatments combined. In California, a leader in developing C accounting guidelines, forest managers must establish a baseline for C stocks. The baseline is calculated as the total C in live and dead trees, coarse woody debris, litter, duff, and live, coarse roots, plus the amount added each year in aboveground growth. Although C stocks in fine roots and soil can be substantial (Post *et al.* 1982; Schlesinger 1995), neither is currently a required pool for calculating a baseline under the California Climate Action Registry Forest Sector Protocol (CCAR FSP; CCAR 2007). Current methodology also requires that harvest stock loss be treated as an emission (CCAR 2007). However, accounting for emissions from wildfire is not required, and if a wildfire does occur, the CCAR FSP requires that the baseline be recalculated for the disturbed site.

Our objective was to model the amount of live- and dead-tree-based C stored and released over a century with and without wildfire in Sierra Nevada mixed-conifer forests, after fuel reduction treatments. Our hypotheses were: (1) in the absence of wildfire, the no-fuels treatment alternative will store the most live- and dead-tree-based C; (2) with wildfire, treatments that develop and retain large trees will store the greatest amount of live-tree C; (3) pre-settlement forest structure will maximize tree-based C storage while minimizing C release during wildfire; (4) with wildfire, prescribed fire treatments will have a lower total C release than unburned treatments; and (5) reducing stand density and concentrating live-tree C stocks in larger individuals will decrease the post-wildfire mortality, reducing the drop below the baseline. Here, we use current CCAR FSP (2007) accounting methods to evaluate changes in C stocks using the Forest Vegetation Simulator (FVS) and track fire emissions using the Fire and Fuels Extension (FFE) of FVS (Crookston and Dixon 2005). Although FVS does not

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account for soil C, it is regionally calibrated, widely used by managers to model forest response to different treatments and disturbances, and one of the CCAR-approved models for establishing baselines.

Methods

We used data collected in the Teakettle Experiment (http://teakettle.ucdavis.edu), in which all trees ≥ 5-cm diameter at breast height (dbh) were measured and mapped in 18 replicate 4-ha plots. Using FVS, we modeled the effects of eight treatments (control, burn only, understory thin, understory thin and burn, restoration thin [based on North *et al.* 2007], restoration thin and burn, 1865 reconstruction, and 1865 reconstruction and burn) on tree-based C stocks. Although not significantly different, pre-treatment forest structure and C stocks varied among Teakettle's 18 plots (North *et al.* 2002). To normalize this difference in the model runs, we randomly chose eight 4-ha plots and applied all model runs to the same eight plots. Mechanical removal treatments were applied to the pre-treatment plot data before the start of model runs, to allow for the individual tree selection that best met treatment goals.

With the exception of the 1865 reconstruction and burn, all treatments that included prescribed fire were burned every 20 years, beginning in 2000. The control and burn-only treatments modeled stand conditions over 100 years without thinning. The understory thin and understory thin and burn, after a widely used Sierran mixed-conifer treatment (Verner *et al.* 1992), removed all trees 25–76 cm dbh in 2000. The 1865 reconstruction used the reconstruction of active-fire stand conditions for the eight plots immediately after the last wildfire (North *et al.* 2007). The 1865 reconstruction and burn added prescribed fire to the treatment every 20 years, starting in 2020 (we excluded the 2000 prescribed fire because reconstructed conditions were immediately after the 1865 fire). The restoration and restoration-and-burn treatments retained all pines (*Pinus lambertiana* and *P jeffreyi*) and removed fir (*Abies concolor* and *A magnifica*) and incense-cedar (*Calocedrus decurrens*) trees from below (smallest sizes first) until plots were reduced to a target of 67 trees ha^{-1} (North *et al.* 2007).

We used the Western Sierra Nevada variant of FVS, an individual-tree growth and yield model (Crookston and Dixon 2005), to predict forest growth response to the eight treatments. We specified that live-tree biomass be calculated using the method described by Jenkins *et al.* (2003), which uses genus-specific, allometric equations, based on a literature survey. The live, coarse-root allometric equations are for "soft woods" and are not genus-specific, because few studies have quantified coarse root biomass (Jenkins *et al.* 2003). To quantify each treatment's baseline, we calculated the starting amount of C in live and dead woody matter immediately after mechanical treatment and tracked changes in these C stocks using a 10-year time step. Under CCAR accounting guidelines, the baseline would be recalculated after a fire event. We did not recalculate each treatment's baseline after fire, because differences between tree-based C stocks and baseline may provide a more complete accounting of the influence of wildfire emissions on each treatment's tree-based C budget.

Fire treatments were simulated and C emission values calculated via the FFE of FVS. FFE uses three sub-models to track standing dead trees and fuels, and to simulate fire intensity and effect on fuels, snags, and live trees (Reinhardt and Crookston 2003). FFE uses existing fire models to calculate the potential surface-fire intensity of user-defined parameters, including slope, fuel moisture, wind speed (6-m above ground), and canopy closure (Reinhardt and Crookston 2003). Surface fire intensity, coupled with the height to live crown, is used to determine torching. The probability of tree mortality from fire is a function of individual tree attributes, including crown scorch (Reinhardt and Crookston 2003). The proportion of tree crown scorched is considered killed and is deposited on the forest floor as fuel during the time step. Tree crowns exposed to fire experience 100% consumption of foliage and 50% consumption of small branch wood (branches < 0.63 cm; Reinhardt and Crookston 2003). The remainder of the unconsumed tree biomass is moved to, and tracked in, the snag sub-model (Reinhardt and Crookston 2003).

We simulated prescribed fire at 20-year intervals to match the historic fire regime for Sierran mixed conifer (McKelvey and Busse 1996; North *et al.* 2005), setting specific prescribed fire conditions to closely match conditions during Teakettle's 2001 prescribed burn: 10 mile per hour (mph) [~16.1 kilometer per hour (kph)] winds, 70° F (~21.1° C) temperature, and moist fuel conditions common during prescribed burns in the fall. To examine each fuel treatment's response to wildfire, we simulated wildfire during the year 2050. Wildfire conditions often occur during high (90th percentile) or extreme (97.5th percentile) weather conditions (Stephens and Moghaddas 2005). We used extreme fire weather conditions that included 40 mph (~64.3 kph) winds, 90° F (~32.2° C) temperature, and very dry fuel conditions. A temperature of 90° F is not uncommon during the warmest part of the summer at the study site (MH and MN personal observation). The 40 mph wind speed is on the upper end of the wind-driven, crown-fire speeds reported by Rothermel (1991) and was chosen to represent a worst-case scenario. Fire emissions within the FFE carbon submodel are calculated via a fire event's biomass reduction at a biomass-to-C conversion factor of 0.37 for litter and duff, and 0.50 for wood (Reinhardt and Crookston 2003; FFE Addendum 2007).

There are limitations in FFE's accounting of fire C release. For example, soil organic matter may be volatilized through burning or translocated after the fire event, as a result of erosion (Breshears and Allen 2002).

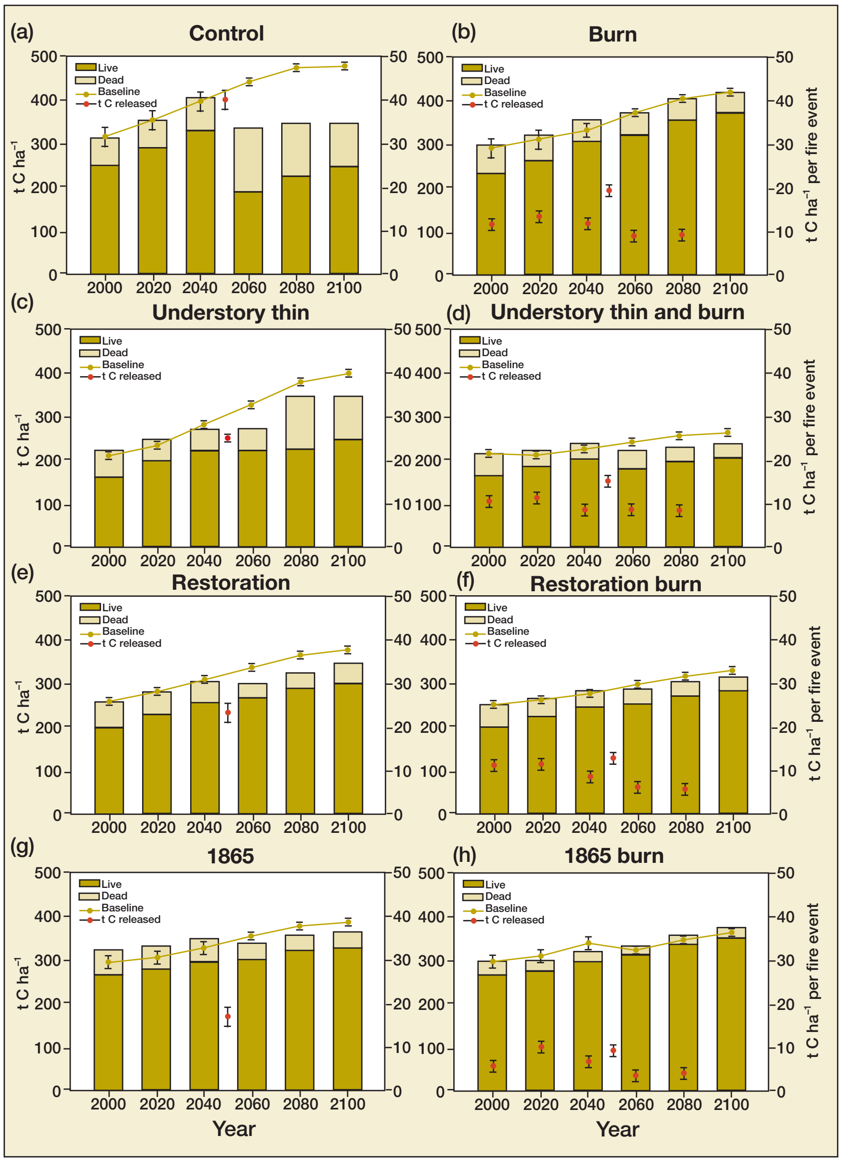

Figure 1. *Tons of C per hectare stored in live and dead tree biomass and released by fire in eight fuel treatments: (a) control, (b) burn only, (c) understory thin, (d) understory thin and burn, (e) restoration thin, (f) restoration thin and burn, (g) 1865 reconstruction, and (h) 1865 reconstruction and burn. Red dots indicate the tons of C per hectare released in the 2050 wildfire and during each prescribed burn event. Baseline dots with standard error bars represent the total aboveground live and dead biomass, starting from the post-treatment stand condition, if the forest did not burn. Baselines in (b–h) can be compared with the control's baseline to assess total changes in C stocks from pre-treatment condition.*

Fire may also form black C that can remain within the forest (Schulze *et al.* 2000; DeLuca and Aplet 2008). Although the FFE module misses these C dynamics, the relative emission differences between treatments should be representative of the different stand conditions that FVS does effectively model.

Results

At the start of the model runs, the 1865 reconstruction had the greatest tree-based C stock. In the absence of wildfire, baseline conditions indicate the control (476.3 t C ha^{-1}) and burn only (417.4 t C ha^{-1}) had the largest tree-based C stocks by 2100 (Figure 1 a,b). With a mid-century wildfire, the burn-only and 1865-burn treatments had the highest tree-based C stocks in 2100 and were the only treatments that continued to meet their respective CCAR pre-wildfire baselines. Treatments that included prescribed burning had tree-based C stocks closest to baseline levels, particularly after the 2050 wildfire (Figure 1). The restoration-burn treatment had the smallest drop below baseline. The proportion of dead to live C tended to increase after fire events and is most influenced by stand stocking levels. High-density stands, such as the control, had a higher proportion of their total aboveground C in dead biomass than did open stands (ie the 1865 treatments), which had a greater proportion of large-diameter, fire-resistant species.

Wildfire emissions were highest in the control (Figure 2) and decreased in order of understory, restoration, and 1865 treatments. Thinning treatments that included prescribed fire had lower wildfire emissions than did treatments that only involved thinning (Figure 2). Stands with a higher percentage of dead biomass had higher wildfire emissions (Figure 1). Over five applications, total prescribed burn emissions were 2–3 times higher than one-time wildfire emissions in treatments that combined thinning and prescribed burning. Prescribed fire emissions correlated with stocking levels, with the burn-only having the highest C release and the 1865-burn treatment having substantially lower emissions (Figure 2). The fire emissions pattern is the same when wildfire emissions are included, with all prescribed-burn treatments having higher totals than their unburned, paired treatment. Harvested trees accounted for 65 t C ha^{-1} and 47.8 t C ha^{-1} removed from the site for the understory and restoration thinning treatments, respectively. This C, however, is not emitted directly to the atmosphere. For a merchantable timber sale such as Teakettle, about 40% may become rapidly decomposed milling "waste" such as sawdust, and 60% can become wood products with a half-life of 1–100 years (Skog and Nicholson 2000).

Thinning trees from small size classes had little impact on tree-based C storage, but did raise the average height from the ground to the base of the live crown, a key factor in reducing fire intensity (Agee and Skinner 2005).

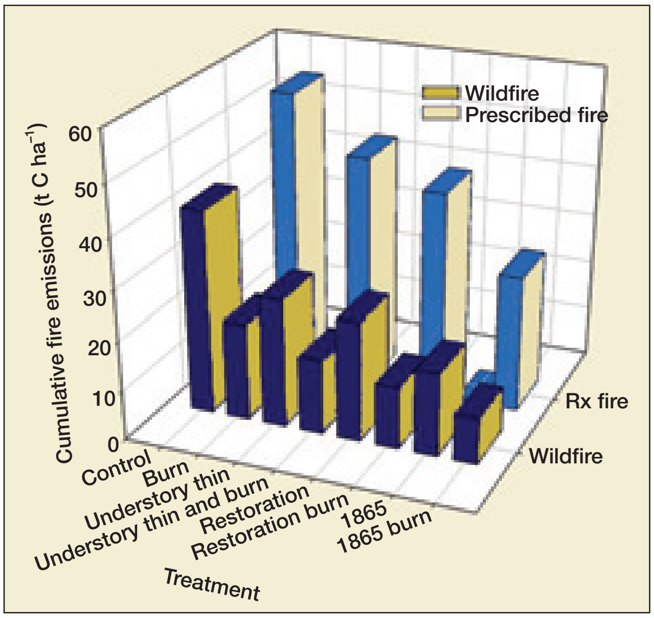

Figure 2. *Total C emissions (t C ha^{-1}) from each wildfire and prescribed burn event for each of the eight treatments. Rx, prescribed.*

Long-term fuels reduction was greatest for restoration and prescribed-burn treatments, because they reduced small-diameter tree densities and shifted composition toward more fire-resistant pines. The most wildfire-resistant treatments, as measured by those with the highest number of large trees (> 75 cm dbh), were the 1865, 1865-and-burn, restoration-and-burn, and burn-only treatments, whereas the control and understory-thin treatments had the fewest (Figure 3). In the intermediate size classes (35–75 cm), the percentage of pine (*P jeffreyi* and *P lambertiana*) is important, because pines are more likely to survive a wildfire than fir (*A concolor* and *A magnifica*) and incense-cedar (*C decurrens*). Only the 1865 and restoration-and-burn treatments had a substantial percentage of pine in the intermediate size classes. All prescribed fire treatments had lower stocking in the more flammable, small-diameter classes, particularly the 15–25 cm class. Stocking levels in small size classes are highest in the control, understory-thin, and restoration-thin treatments, suggesting that these are susceptible to more combustion and C release in future wildfires.

Discussion

In flammable forests, sequestering C is more complex than maximizing stocking levels and mean annual growth increments. There are trade-offs in emission and storage rates, depending on treatment application and wildfire timing as stands develop. However, the consistently high storage and low emissions of the 1865 reconstruction suggest that a low-density forest, dominated by large, fire-resistant pines, may be a desired stand structure for stabilizing tree-based C stocks in wildfire-prone forests.

Current accounting practices only examine tree-based C, without considering the substantial proportion of C in soils and in fine-root turnover (Garten Jr *et al.* 1999). Although belowground C estimates are difficult and current methodologies need refinement (Strand *et al.* 2008), a more complete accounting would consider fuel treatments and wildfire effects on these stocks. In the interim, forest managers will have to focus on tree-based C: stocks that can be manipulated to influence C accumulation and long-term storage. Currently, changes in C stocks are calculated at the typical management scale of a forest stand. Calculating changes in a landscape's C stock would be more compatible with our understanding of fire probabilities and burn behavior. Many landscapes, however, are divided by ownership/management boundaries, making large-scale C accounting difficult within the current cap-and-trade approach.

The CCAR's current accounting methods do not require forest managers to report wildfire emissions; they are only required to adjust the forest baseline. A more complete accounting would include C released from fire events, similar to the IPCC (2006) guidelines. Under this accounting, which includes wildfire emissions, our model runs suggest that a forest structure that is resistant to stand-replacing fire would not differ substantially from its baseline. Modeled future California climate conditions suggest that rises in temperature and increasing growing season length are likely to occur (Cayan *et al.* 2008), and that these changes may increase the number of large fire events (Westerling *et al.* 2006). Given the frequency of fire occurrence in pre-settlement forests, during a relatively cool, moist period (Taylor and Beaty 2005), and the predicted shifts in climate, untreated forests are likely to have lower tree-based C stocks than more fire-resistant forest structures.

When prescribed fire is used to reduce wildfire severity, there are trade-offs in smoke and C emissions. Prescribed fire consumes forest-floor fuels, including litter and duff, which can be a major contributor to total wildfire emissions (Campbell *et al.* 2007). Individual, direct prescribed-burn emissions were low, ranging from 4.5 to 18 t C ha^{-1} (Figure 1), but when totaled over a century and added to the wildfire emissions, total released C was greater than that in the no-burn treatments (Figure 2). Recent research suggests that immediate wildfire emissions may only be a portion of actual C losses, if the fire leaves few surviving trees (Kashian *et al.* 2006). Auclair and Carter (1993) calculated that high-intensity, post-wildfire C release was approximately three times the direct release of CO_2 during the fire event. In ponderosa pine, direct flux measurements found higher CO_2 emissions from a high-intensity burn than those from an unburned site, even 10 years after fire (Dore *et al.* 2008). Future research may more effectively incorporate these C losses associated with high-intensity fire into models, but, in this paper, we compare only direct C emissions occurring during the fire.

Although the addition of prescribed fire does result in higher total direct emissions, it has some advantages. Prescribed fire reduces wildfire intensity, can be lit when crews are available, and affords some control over smoke drift. Stand conditions by treatment in 2100 (Figure 3) also suggest that prescribed fire is an effective treatment for moving forest structure toward a more fire-resistant condition. Similar to some thinning treatments, prescribed fire not only reduces competition and "releases" residual tree growth, but can also accelerate large pine development with a post-fire nutrient pulse and selective mortality of smaller-diameter, fire-sensitive species (eg restoration versus restoration-and-burn treatments in Figure 3 e,f).

In our simulations that included wildfire, tree-based C stocks in 2100 are strongly affected by stand structure produced by the initial fuel treatments. Treatments that reduce the number of small-diameter trees, which act as ladder fuels, reduce emissions (Figure 3) and the mortality of large trees. In simulations varying wildfire timing (ie 2020–2090), intermediate (35–75 cm dbh) tree survival increased with interval length, but emissions also increased substantially. The low density of the 1865 reconstruction consolidates increment growth in large, fire-resistant trees, while maintaining fewer small trees (Figure 3). The restoration-and-burn treatment (Figure 3f) is the best option for approximating the 1865 forest structure and species composition, conditions that should be fire resistant. We caution, however, that our modeling focus is on stands exposed to a simulated, uniform wildfire event. Wildfire effects on forest conditions and C emissions will vary across a burn landscape in response to local fuel conditions and the interaction of fire behavior and weather. We have not attempted to model this more complex fire dynamic and instead have focused on the scale at which managers often manipulate forest structure and use different fuel treatments.

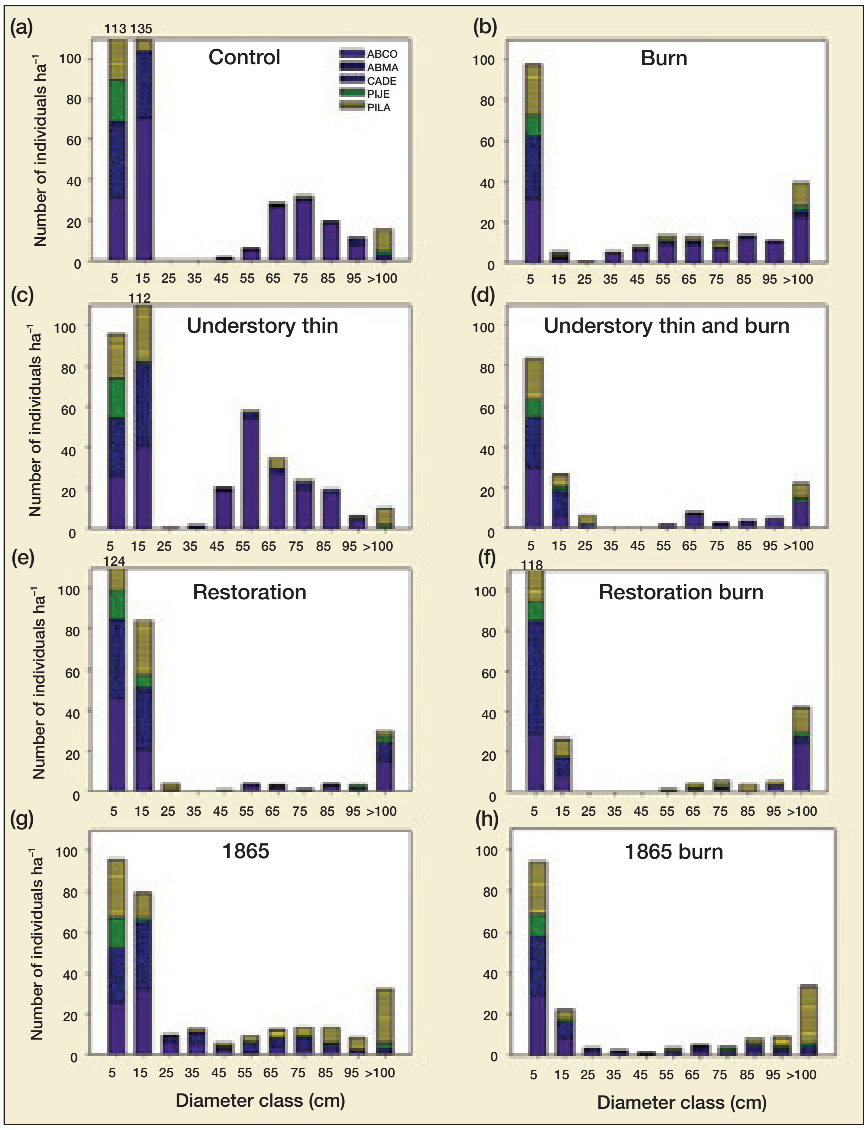

Figure 3. *Diameter distributions by species in the year 2100 for the eight fuel treatments: (a) control, (b) burn only, (c) understory thin, (d) understory thin and burn, (e) restoration thin, (f) restoration thin and burn, (g) 1865 reconstruction, and (h) 1865 reconstruction and burn.* A concolor, *ABCO*; A magnifica, *ABMA*; C decurrens, *CADE*; P jeffreyi, *PIJE*; P lambertiana, *PILA*.

Forest C sequestration has been proposed as a way to help offset other anthropogenic CO_2 emissions (Woodbury *et al.* 2007). In forests that historically burned with high frequency and low severity, adding to the C baseline by increasing stocking levels may exacerbate the modern shift toward high-severity fire produced by fire suppression and climate change. Current C accounting practices can be at odds with efforts to reduce fire intensity in many western US forest types. Although the concept of restoring forests in the western US to some pre-settlement target may not be feasible as the climate changes, reducing fire severity and increasing and stabilizing tree-based C storage may be achieved with fuel treatments that promote low-density, large pine-dominated stand structures.

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