A gap-based approach for regenerating pine species and reducing surface fuels in multi-aged mixed conifer stands in the Sierra Nevada, California

ROBERT A. YORK¹,²*, JOHN J. BATTLES², REBECCA C. WENK² AND DAVID SAAH³

¹Center for Forestry, University of California Berkeley, 4501 Blodgett Forest Road, Georgetown, CA 95634, USA
²Department of Environmental Science, Policy, and Management, University of California Berkeley, 130 Mulford Hall, UC Berkeley, CA 94720-3114, USA
³Spatial Informatics Group, LLC, 3248 Northampton Ct, Pleasanton, CA 94588, USA
*Corresponding author. E-mail: ryork@berkeley.edu

Summary
Multi-aged stands in a mixed conifer forest of California were treated to mitigate harvest-related increases in surface fuels and to prepare sites for natural regeneration of Pinus species. The study was designed to (1) assess effectiveness of small gap fuel treatments (piling and burning in 0.04 ha gaps) on surface fuel and modelled fire behaviour; (2) test the effect of substrate quality on germination of Pinus species; (3) measure the influence of gap creation on light availability and stand-level light heterogeneity. While the fuel treatment only covered 10 per cent of stand area, it was effective in avoiding increases in stand-level surface fuel following harvests. Fire behaviour was predicted to be moderate following the treatments. The harvest coupled with the gap surface fuel treatments did not change predicted fire behaviour compared with the pretreatment stands. There was a significant but variable increase in germination of Pinus ponderosa seed when sowed on ash substrates compared with bare soil. No substrate effect was detected for Pinus lambertiana. The 0.04-ha gaps created distinct pockets of light and greatly increased stand-level light heterogeneity. This gap-based approach to regenerating multi-aged stands coupled with small-scale fuel treatments is promising for reducing fire hazard and regenerating shade-intolerant species.

Introduction
Silvicultural systems that promote multi-aged stands through periodic diffuse harvests are a viable option under modern landscape management regimes attempting to emulate natural disturbances (Long, 2009). Within a framework of large-scale ecosystem management, such systems can be a means for achieving heterogeneous forest structures at the stand level (North et al., 2009; Puettmann et al., 2009). Smaller landowners may gain several additional benefits from multi-aged systems. For example, artificial regeneration costs are lower or do not exist, canopies remain relatively intact throughout time to provide continuous soil protection and productive capacity and income from harvests can be spread out to provide revenue at relatively short intervals (Mathews, 1992). For some landowners, multi-aged systems may actually be the only regeneration option that is permissible because of legal agreements restricting even-aged methods (i.e. easements) or because of local forest practice regulations governing small landowners. Finally, there is potential for multi-aged stands created by harvesting individual or small groups of trees to have long-term productivity rates comparable to even-aged stands (O’Hara and Nagel, 2006; Laiho et al., 2011). While the benefits listed above for some forests may be rooted in biophysical processes or management efficiencies, there also exists a general social perception that multi-aged stands are ‘more natural’ and therefore inherently preferable (O’Hara et al., 2007). As O’Hara et al. (2007) has noted, however,
the degree to which objectives are met should be measured in order to ultimately assess a multi-aged system's value.

Opposing the benefits of multi-aged systems are several risks (Guldin, 1996). A concern often mentioned by forest managers is the tendency for poor regeneration of pioneer tree species (i.e., shade intolerants) if too much canopy cover is retained or if seed dispersal from desired species does not happen to coincide with harvests. Another is that an unprepared seedbed (i.e., decomposing and fresh litter on forest floors) will restrict germination of some species, especially pioneer tree species that germinate on heavily disturbed forest floors. This lack of control over species composition is a substantial risk, especially when compared with the high degree of species control in even-aged systems. In forests where wildfires are common, there is an additional and profound risk of catastrophic loss, especially if intermediate-sized trees (i.e., 'ladder fuels') and surface fuels increase as a result of selective harvests (Agee and Skinner, 2005).

In mixed conifer forests of Western North America, the effects of multi-aged systems on species composition and surface fuels are of particular importance. Ponderosa pine (Pinus ponderosa var. ponderosa Doug. ex. Laws) regeneration requires disturbances that substantially reduce competition and prepare a disturbed seedbed for germination (Oliver and Ryker, 1990). Sugar pine (Pinus lambertiana Doug.), while not as tightly linked with disturbance as ponderosa pine, also regenerates more readily following disturbances (Kinloch and Scheuner, 1990). Sugar pine can also be an especially high-priority species to regenerate in order to assist population recovery from impacts of the exotic pathogen, white pine blister rust (Cronartium ribicola Fischer, van Mantgem et al., 2004). Shade tolerant species such as white fir (Abies concolor (Gord. & Glend.) Lindl. ex Hildebr.) and incense-cedar (Calocedrus decurrens Torr.), meanwhile, have been increasing in stands with low management intensities and where fire-exclusion policies prevail (Ansley and Battles, 1998; Pierce and Taylor, 2010).

Fire severity in mixed conifer forests of Western North America has been increasing (Westerling et al., 2006; Miller et al., 2009) and proactive management to reduce fire hazard is being urged (Collins et al., 2010). Traditional methods of applying multi-aged systems, however, may fall short in achieving either desired species compositions or in reducing fire hazard. Following harvests, site preparation activities that dispose of activity fuel (i.e., logging slash) and prepare seedbeds to encourage germination typically do not occur, leading to potential increases in surface fuel loads that are especially important in driving fire behaviour (Agee and Skinner, 2005). If multi-aged systems increase surface fuel loads and encourage regeneration of only tolerant species, they may be more diminished in meeting health and diversity objectives than forests where fire suppression is the only management activity (Stephens and Moghaddas, 2005b).

Novel approaches are clearly needed to meet modern objectives while using multi-aged systems. One approach is to harvest in a dispersed manner throughout stands, as would traditionally occur, but also manage specific areas within stands for both fuel reduction and seedbed preparation for pine regeneration. By creating small canopy gaps during a harvest, then piling and burning debris within gaps, a high-quality seedbed of ash and/or bare soil could be created while simultaneously reducing surface fuel. Such an approach could potentially maintain the essence of multi-aged systems (stand-level heterogeneity and multiple age classes), while also addressing concerns of low pine regeneration and surface fuel build-ups. Given that pine species in pre-settlement Sierra Nevada forests likely regenerated in distinct canopy gaps created by flare-ups in mixed-severity fires (Keeley and Zedler, 2000), it follows that higher germination rates in canopy gaps with ash substrates could be an adaptive trait. There is limited information from sowing studies to verify this, however (but see Zald et al., 2008). While there have been studies finding correlations between different substrate types and the presence of established conifer seedlings (e.g., Gray et al., 2005), these studies have not measured substrate type at the time of germination, which may have occurred several years earlier. This discrepancy is important because the availability of suitable germination sites precisely coincident with seed dispersal is a dominant influence on mixed conifer regeneration in the Sierra Nevada (North et al., 2003; van Mantgem et al., 2006). Information about substrate effects on germination of different species is therefore critical for designing multi-aged systems that rely on natural regeneration following regeneration harvests.

This study has three objectives. One is to present a case study on the feasibility and effectiveness of a pile-and-burn fuel reduction treatment in terms of reducing surface fuel and modifying predicted fire behaviour within multi-aged stands. Fuel treatments were concentrated in small canopy gaps dispersed throughout two multi-aged stands in a central Sierra Nevada mixed conifer forest. The second objective is to measure the influence of ash versus soil substrates on germination of ponderosa pine and sugar pine from a controlled seed-sowing experiment within canopy gaps created with multi-aged regeneration harvests. The third objective is to evaluate the influence of introducing canopy gaps on light heterogeneity and availability in the context of encouraging pine regeneration. We focus on informing management by evaluating the effectiveness of applying treatments in multi-aged stands to coincidentally reduce surface fuels and encourage regeneration of pine species.

Methods

Study area and treatments

The study was located at the University of California, Berkeley’s Blodgett Forest Research Station (BFRS), in the central Sierra Nevada Mountains (1300 m elevation; 38° 52′ N, 120° 40′ W). The climate is Mediterranean, with annual precipitation (average = 166 cm) occurring mainly during the winter and spring months and a prolonged drought during the summer. Soils are well developed, originating from granodiorite parent material. Heights of codominant anopy trees typically reach 27–34 m in 50–60 years.
Vegetation at BFRS is dominated by a mixed conifer forest type (Fites-Kaufman et al., 2007), composed of variable proportions of white fir, incense-cedar, Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco var. menziesii), ugar pine, ponderosa pine and California black oak (Quercus kelloggii Newb.).

The treatment was conducted within two stands at BFRS (stands 230 and 110) ~1.5 km apart. Both stands have slight slopes, generally less than 15 per cent. Each stand has had several harvest entries on a roughly 10-year interval since the early 1970s. Harvests have removed individual trees of all size classes dispersed throughout the stands. As a result of the multiple harvest entries, stand structures are highly heterogeneous with multiple age and size classes present. Past harvest operations have all used conventional manual felling with chainsaws and ground-based yarding present. Past harvest operations have all used conventional manual felling with chainsaws and ground-based yarding.

In general, harvests occur in these stands when basal area densities surpass a predetermined upper threshold (~50 m² ha⁻¹). Harvests reduce basal area density by ~40 per cent. Density therefore fluctuates over time within this density management zone of 30–50 m² ha⁻¹. This target has corresponded to a harvest about every 10 years in both stands used for this study. Forests with lower productivities or different desired harvest frequencies could have lower and/or wider density management zones. The harvests for this study were designed to remove trees of all size classes, in proportion to the growing space occupied by each size class. In addition to the harvest of individual trees throughout stands, ~10 per cent of each stand area was converted to 0.04-ha canopy gaps, distributed throughout the stands. Within these 0.04 ha areas, all merchantable trees were removed.

Stand 230 is 17 hectares, which given the 10 per cent gap conversion rate described above, corresponded to ~42, ~0.04-ha gaps created during the harvest. Of these, 30 were used for the study. Stand 110 is 18 hectares, corresponding to 45 gaps, of which, 35 were used in the study (the biggest and smallest gaps were excluded in both stands). The harvest in stand 230 took place in the summer of 2004. The harvest in stand 110 took place in the summer of 2006. The same experimental design was used in each stand. Only the timing of the treatment was different (along with differences in climate between the two periods). Because of the difference in treatment timing between stands, they were considered two different trials of the same experiment rather than replications of a single treatment.

Following the harvest of merchantable trees, non-merchantable trees (<25 cm diameter growth at breast height (d.b.h.)) within gaps were cut and placed into a pile at gap centre. Surface fuels within gaps were also collected and placed into piles. A tracked excavator with a grapple head was used for the non-merchantable tree removal and piling in each gap. Debris piles were burned during the fall after each harvest. Burning followed ~10 cm of cumulative precipitation after the summer drought period. Piles were lit during the morning and then allowed to burn all day before throwing any unburned pieces on pile edges into pile centres by hand to increase consumption. The same operator for machine piling and the same hand crews for burning were used in both stands. The piling and burning activity within these gaps was similar to a typical site preparation operation following a regeneration harvest in an even-aged stand but on a much smaller spatial scale.

The seed-sowing experiment was designed to isolate substrate quality as a factor of germination frequency. Seeds were sown in the fall within gaps after the burned areas had cooled completely. Seeds were collected from several parent trees throughout BFRS in previous years during good cone crops and stored in a seed storage facility. Prior to sowing, seeds were stratified by soaking them in running water for 48 h, similar to the protocol used by nurseries prior to sowing. This served to emulate the soaking that the seeds would have received had they been dispersed from parent trees surrounding the gaps in late summer. Seeds were sown within gaps on three different substrates: ash, ash/soil edge and bare soil (Figure 1). For each of the three substrates, two sowing spots were located within 1 m of each other, one for ponderosa pine and one for sugar pine. Five seeds were sown at each sowing spot. Seeds were embedded into the sowing substrate by hand so that all or most of the seed were buried within 1 cm of the surface. All five seeds were sown within a 10 × 10 cm area. Pine seeds are relatively large and many, if not most, dispersed seeds are collected and cached by small mammals (Vander Wall, 1994). To prevent seed predation and relocation, ‘seed caps’ made from metal mesh were secured over the sown seeds. Wire stake flags were used to mark sowing locations. Four hundred and fifty seeds of each pine species were sown in stand 230 (30 gaps × 3 sowing spots × 5 seeds per spot), while 525 seeds of each species were sown in stand 110 (35 gaps).

There is a potential confounding effect in this seed-sowing design that could be caused by a centre-to-edge gradient in

![Figure 1. Seed sowing locations within ~0.04-ha gaps within multi-aged stands at Blodgett Forest Research Station, California.](http://forestry.oxfordjournals.org/)
microclimate along the line of substrate treatments from ash to soil (Figure 1). If edge environments are shadier, then germination might be different at ash substrate locations because of a direct influence of radiation on germination. To assess this potential, we measured the per cent of total transmitted radiation at north edge and central locations of 14 randomly selected gaps in stand 230 with hemispherical photography (see methods for light measurements below) to see if such a gradient existed. The mean per cent of total transmitted radiation reaching gap centres was 39 per cent, while radiation at north edges of gaps was 42 per cent. These means were statistically indistinguishable (two-tailed $t$ test $P = 0.44$). The actual difference in light between ash and soil substrate sowing locations is even less than this 3 per cent non-significant difference since the substrate treatments were oriented along an east–west line and not a south–north line where the light gradient in gaps is steepest (Canham et al., 1990; York et al., 2003). Furthermore, seeds were not sown at gap edges but well within the perimeters of gap boundaries as projected by the drip-lines of the surrounding canopy. Within-gap differences between sowing locations other than those caused by the substrate treatment are therefore not considered to be confounding.

**Measurements and analysis**

The influence of within-gap fuel treatments on stand-level surface fuels was measured with line-intersect transects (Brown, 1974). Sampling points were distributed throughout the stands on a 120-m square grid and measured prior to harvests, then again after the harvests and fuel treatments described above. There were 13 sampling points in stand 230 and 14 points in stand 110. Sampling points were used whether or not they overlapped with a gap (i.e. they measure net change in stand-level fuels). At each sampling point, two transects were measured. The first was oriented in a random direction and the second oriented positive 60 degrees from the first. Because surface fuels are often variable within stands (e.g. Reiner et al., 2009), the two transects were averaged to increase precision at the level of the sampling point. One-hour (0–0.64 cm) and 10-h (0.64–2.54 cm) fuels were intercept-sampled from 0 to 2 m, 100 h (2.54–7.62 cm) fuels from 0 to 3 m and 1000 h (>7.62 cm) and larger fuels from 0 to 11.3 m along transects. Duff and litter depth were measured at 0.3 and 0.9 m on each transect. Fuel depth was measured at three points along each transect. Fuel loads were calculated using equations developed for local species (van Wagendonk et al., 1996, 1998).

The objective of the surface fuel analysis was to quantify the effect of treating surface fuels using this gap-treatment approach in multi-aged stands. The fuel treatment was not an experimental treatment, per se (with different levels of fuels treatment intensity, for example). To determine the net effect of the fuel treatment on surface fuel load at the stand level, we compared the means of total fuel loading before and after the harvest. Comparisons were done separately for the two stands. The 95 per cent confidence interval of the difference between means and the magnitude of change in total fuel load following treatments was the basis for inference.

We followed the approach used by Stephens and Moghaddas (2005a) to evaluate changes in fire behaviour associated with harvest treatments. Since our goal was to evaluate a worst-case scenario with respect to fire hazard, we modelled fire behaviour responses under extreme fire weather with Fuels Management Analyst (FMA) Plus, Version 3 (Carlton, 2005). We used the fire weather parameters calculated for Blodgett Forest that represent extreme (97.5th percentile) conditions observed during the last 41 years at a nearby weather station (values reported in Table 1 in Stephens and Moghaddas, 2005a)). FMA Plus relies on site-specific information on fuel loading and forest structure to estimate stand-level fire behaviour. Surface fuels (e.g. leaf litter, forest duff and coarse woody debris) provide the substrate that carries fire and determine fire intensity and spread rate. Canopy attributes (e.g. crown bulk density, crown base height and vertical continuity) influence the probability of a crown fire and subsequent tree mortality. Forest structural attributes such as canopy cover and tree height modulate wind speeds and fuel moisture that in turn influence fire behaviour (Pierce et al., 2009). FMA Plus incorporates field-based measurements of these key factors and uses published methodologies to compute fire behaviour and effects for given fire weather conditions (Stephens and Moghaddas, 2005a). We developed the necessary inputs for FMA Plus from the pretreatment and posttreatment field measurements of surface fuels and trees.

| Fuel component | Pretreatment | Posttreatment | Pretreatment | Posttreatment |
|----------------|--------------|---------------|--------------|---------------|
| Duff           | 113.4 (16.9) | 98.7 (17.0)   | 37.3 (4.3)   | 37.1 (8.2)    |
| Litter         | 42.4 (3.8)   | 21.7 (3.3)    | 20.3 (2.7)   | 16.4 (2.5)    |
| 1 h            | 0.9 (0.2)    | 0.9 (0.2)     | 0.7 (0.2)    | 1.0 (0.2)     |
| 10 h           | 3.3 (0.5)    | 2.7 (0.4)     | 2.6 (0.6)    | 4.5 (0.7)     |
| 100 h          | 10.3 (2.7)   | 7.7 (1.5)     | 5.0 (1.4)    | 11.7 (2.5)    |
| 1000 h         | 5.0 (1.8)    | 3.3 (1.3)     | 3.6 (1.4)    | 3.7 (1.3)     |
| Total fuel load| 202.0 (23.4) | 135.1 (18.2)  | 69.4 (6.9)   | 74.5 (10.4)   |
| Fuel depth     | 15.0 (2.8)   | 5.6 (2.3)     | 2.0 (0.7)    | 9.3 (2.4)     |
Similar approaches have been used throughout the dry forests of the western US to evaluate the efficacy of fuel treatments on wildfire effects (Hartsough et al., 2008).

Sown seeds were monitored for germination starting in the spring after the fall sowing. Surveys started immediately following snow melt and, in both stands, timing of the start of survey was ideal for capturing the first germination events because snow had just recently melted. Surveys began on 6 May 2005 in stand 230 and on 23 April 2007 in stand 110. In stand 230, surveys occurred every 2 weeks until no new germinants were found (June 22nd) and then, a final survey was done 1 month later to ensure capture of any late germination. In stand 110, surveys were done every month until no new germinants were found, followed 1 month later by a final survey. Following the experience of surveying in stand 230, 1-month intervals were found to be adequate for the purpose of this study because germinating seeds were protected from predation by the mesh covers and germinating seeds did not decompose or otherwise disappear within any 1-month period. A seed was considered germinated if the hypocotyl had breached the seed coat and made contact with the soil. During surveys, the number of germinants at each spot was recorded. Following the final survey, the cumulative number of germinants occurring at each spot was summed. Zero to five germinants were possible at each spot.

The objective of the germination analysis was to describe the relationship, if any, between substrate type and germination frequency. Our primary interest was in finding any effect, positive or negative, of the ash substrate on germination compared with the bare soil substrate. When no seeds germinated in a given sowing location, the germination frequency was zero. These zero values were particularly important in this case to keep as zero values (as opposed to adding one and doing a data transformation) since zero germination was an ecologically distinct event and not simply zero germination frequency. Our primary interest was in finding any effect, positive or negative, of the ash substrate on germination compared with the bare soil substrate. When no seeds germinated in a given sowing location, the germination frequency was zero. These zero values were particularly important in this case to keep as zero values (as opposed to adding one and doing a data transformation) since zero germination was an ecologically distinct event and not simply a very small number along a continuous range of numbers. Germination frequency was therefore modelled as a polytomous response variable (i.e., an ordinal variable), with six levels of germination frequency possible (either 0, 0.2, 0.4, 0.6, 0.8 or 1.0, corresponding to the number of germinants found at each sowing spot). Substrate (ash, soil or edge) and species (ponderosa or sugar pine) nested within the two stands were the predictor variables of interest. Gap (65 levels) was included as a variable to account for variability among gaps. Logistic regression was used to detect significant effects of the predictor variables (Trexler and Travis, 1993). Likelihood ratio tests comparing the full model with all variables to the model without a given variable were used to verify significance. The critical $\alpha$-value to compare with the $\chi^2$-statistic was 0.05. Post hoc tests were done for significant effects from the saturated model with logistic regression and likelihood ratio tests. Analyses were done with JMP software (SAS Institute Inc., Cary, NC).

In addition to the light measurements within gaps in stand 230 described above, we measured stand-wide light availability from a grid both before and immediately after the harvest in order to characterize the change in the light environment across the stand. This was done to assess the effectiveness of the treatment in producing stand-level heterogeneity in light conditions and to find out if the created gaps had more light available within them compared with the stand in general (i.e., to find if they were ecologically distinct areas with respect to increased light availability for encouraging pine regeneration). Photos were collected from the same 120-m sampling grid ($n = 13$) as the fuel measurements using a Nikon 35-mm camera and a Nikkor fish-eye lens (8 mm f/2.8) placed 1 m aboveground. To provide a reference for how light conditions within the harvested stands compare with unharvested reserve stands, we also collected photos from a similarly spaced grid ($n = 35$) in an adjacent stand that has not been harvested for 100+ years. These measurements provide a context for what light conditions would be like in these stands if no harvests had ever occurred. Photos were taken near dawn or dusk to minimize direct lighting effects. Colour slides were converted to digital images (900 d.p.i.) that were analysed with GLA software (Frazer et al., 2000) to compute the per cent of total transmitted photosynthetically active radiation (per cent Total Transmitted Radiation). This index of irradiance calculated from film-based hemispherical photographs has proven to be one of the most reliable measures of light influence on seedling growth (Kobe and Hogarth, 2007). We obtained a precision estimate of ±2 per cent from remeasurement of a random subset (7 per cent) of photos.

Randomization tests were performed to test if the harvest created an overall change in the light environment at the stand level. Means and standard deviations (SDs) from grid measurements prior to and following the harvest were calculated for each of 1000 iterations (random sampling with replacement). Differences (pre- versus post-harvest) in the mean and SD were considered significant when $P < 0.05$. The use of randomization tests provided a common approach to statistically evaluate the impact of the treatments on both the magnitude (mean) and heterogeneity (SD) of the light environment while also accounting for any non-normality in the observed data. The other comparison of interest for statistical testing was between within-gap locations and the stand in general (including both gap and non-gap areas). Light in the unharvested reserve stand is not analysed with statistical tests but the stand’s light data distribution is given to provide an example of the light environment for a stand not having any recent harvest or canopy disturbance.

**Results**

Prior to harvest, both stands had similar structures with mean forest basal area equal to 55 $m^2$ ha$^{-1}$ and mean tree d.b.h. = 40 cm. However, the surface fuel loading in stand 230 was considerably heavier pre-harvest compared with stand 110 (202 tons ha$^{-1}$ versus 69.4 tons ha$^{-1}$, Table 1). Following the harvest and the within-gap fuel treatment, stand-level fuel load decreased in stand 230 compared with the pre-harvest amount by 33 per cent to 135.1 tons ha$^{-1}$ (Table 1), a moderate decrease (33 per cent) that was statistically significant ($P < 0.05$). In contrast, the treatments had no influence on surface fuel in stand 110. Following
Table 2: Predicted wildfire behaviour before and after gap harvests followed by fuel treatments in multi-aged stands at Blodgett Forest, California

| Treatment               | Stand 230 Pretreatment | Stand 230 Posttreatment | Stand 110 Pretreatment | Stand 110 Posttreatment |
|-------------------------|------------------------|-------------------------|------------------------|-------------------------|
| Flame length (m)        | 0.6                    | 0.5                     | 0.2                    | 0.9                     |
| Fireline intensity (kW m⁻¹) | 803.9                | 514.5                   | 128.6                  | 2025.9                  |
| Rate of spread (m min⁻¹) | 1.2                    | 0.9                     | 0.4                    | 2.1                     |
| Torching index (km h⁻¹) | 388.6                  | 617.5                   | 1156.8                 | 166.9                   |
| Crowning (km h⁻¹)       | 45.4                   | 49.2                    | 54.8                   | 49.1                    |

Harvests had only minor impacts on fire behaviour and fire effects. Even under the most extreme fire weather conditions, these managed stands were at low risk of experiencing destructive crown fires. In both compartments, regardless of treatment, surface fires dominated (Table 2). The flame lengths of the modelled fires were all <1 m, well short of the base of the live crown in these stands (none lower than 5.8 m). The predicted plot-level tree mortality rates associated with these low intensity, slow moving fires ranged from a high of 42.6 per cent (standard error (SE) = 3.7 per cent) in Compartment 110 after treatment to a low of 36.2 per cent (SE = 2.4 per cent) in Compartment 230 after treatment. In no case did the harvest treatments cause a significant increase in fire-related tree mortality (t test, P-values > 0.37).

Seed germination was different between stands (i.e. years), species and gaps. Within stands, substrate type (P = 0.001) and species (P < 0.001) were significant predictors of germination frequency in the model, with species having the majority of the influence (Table 3). In stand 230, there was little germination of ponderosa pine at all. Only 20 of the 90 sowing spots had any germinants. Despite the low overall germination in stand 230, however, there was a clear trend towards more germination occurring in ash substrates compared with soil substrates (P = 0.009; Figure 2). In stand 110, ponderosa pine germination was much more common, with 88 of 105 sowing spots having at least one germinant and no clear trend in germination frequency between substrates (P = 0.09).

For sugar pine, there was also a distinct difference in overall germination between the two stands. Interestingly, however, it was the opposite of ponderosa pine. Germination was much more frequent in stand 230 (64 of 90 spots had at least one germinant), while it was considerably lower in stand 110 (32 of 105 spots). There was no detectable

Table 3: Factors of seed germination following sowing of *Pinus ponderosa* and *Pinus lambertiana* seeds on ash and bare soil substrates beneath harvested canopy gaps at Blodgett Forest, California

| Variable   | d.f. | Likelihood ratio χ² | Significance |
|------------|------|----------------------|--------------|
| Gap        | 63   | 177.7                | <0.001       |
| Substrate  | 4    | 18.2                 | 0.001        |
| Species    | 2    | 246.4                | <0.001       |
| Substrate × species | 4 | 4.7                 | 0.31         |

Substrate, species and substrate × species variables are nested within the stands.

Figure 2. Mean germination frequency per sowing spot in stand 230 (A) and stand 110 (B) at Blodgett Forest Research Station, California. Error bars are SEs.
A GAP-BASED APPROACH IN MULTI-AGED MIXED CONIFER STANDS

relationship between substrate and germination frequency in sugar pine in either stand (stand 110, $P = 0.60$; stand 230, $P = 0.53$; Figure 2).

Prior to the harvest in stand 230, the average light reaching 1 m above the forest floor across the stand was 12 per cent of total transmitted radiation, compared with 6 per cent in the unharvested reserve. Light heterogeneity in both the reserve and the treated stand prior to harvest was relatively low (Figure 3). The harvest increased stand-level light to 26 per cent ($P = 0.002$) and increased SD in light from 4 to 13 per cent; the range of light availability levels was dramatically increased (Figure 3). Mean light within gaps (40 per cent) was well above the stand mean of 26 per cent ($P = 0.002$). A difference in SD was not detected ($P = 0.56$) between gaps (9 per cent) and the stand in general (13 per cent). The effect of the harvest was, in general, to increase the amount and heterogeneity of light across the stand. The creation of gaps created distinct pockets of increased light availability nested within the stand.

Discussion

Effectiveness of fuel treatment

Although the fuel treatment following the harvest was restricted to small areas dispersed throughout the stand and covered only 10 per cent of the total area, the treatment was effective in avoiding a net increase in stand-level surface fuel following conventional harvesting methods that left all tops and limbs of harvested trees on-site. Where surface fuel load was particularly high prior to harvest, the treatment actually resulted in a net decrease in surface fuel following the harvest.

In general, we found that these stands to be exposed to only modest fire hazard following the harvest and fuel treatments. The multi-aged prescription maintains a heterogeneous canopy structure with much of the productivity concentrated in large diameter trees. Clearly, surface fuels are a concern given their important role in determining fire behaviour (Agee and Skinner, 2005). However, despite the potential to accumulate high surface fuel loads, particularly in the 10- and 100-h size classes (Table 1), there were limited ladder fuels to carry modelled fires into the canopy. While the treatments resulted in increased modelled fire line intensity and rate of spread (Table 2) relative to pre-treatment conditions, the modelled fire never got off the surface and never caused widespread mortality. Stephens and Moghaddas (2005a) reached a similar conclusion regarding the efficacy of mechanical thinning treatments at modifying fire behaviour in these forests.

In situations where there is an especially large amount of surface fuel (similar to stand 230 in this study), the modest decrease in surface fuels that were achieved in this case might not be enough for managers wanting to reduce fire hazards to very low levels. Options for further reducing surface fuels in multi-aged stands include more intense treatments (either prior to or following harvests) that cover more than 10 per cent of the stand area or using a different yarding method to reduce activity fuel. Whole-tree
harvesting, in particular, could transport tops and limbs to landings rather than leave them in the stand as surface fuel (Schmidt et al., 2008).

The effectiveness of fuel treatments to a large degree depends on the details of how treatments are carried out. During the treatments for this study, only 10 per cent of the stand area was treated but more than 10 per cent of the slash present following the harvest was actually piled. The debris piles were made within 0.04-ha gaps, where high concentrations of slash resulted from the harvest of a clump of adjacent trees. This resulted in higher amounts of slash within gaps compared with the stand in general. During the treatments for this study, the operator did not distinguish between fresh logging slash and slash that had been created by previous operations or debris that had fallen on its own. More than just recent activity fuel created by the harvest, therefore, was piled and burned.

Substrate effects on pine germination

When ponderosa pine germination was in general more frequent, it made no difference whether the substrate was ash or soil. However, ponderosa pine germinated more frequently in the ash substrate when germination was in general low. This tendency towards slightly higher ponderosa pine germination in ash substrates was noted long ago in a nursery experiment (Fisher, 1935). More recently, an increase in germination on ash substrates was noted for Jeffrey pine, a species very similar to ponderosa pine (Zald et al., 2008). Our interpretation is that ash substrates are not likely to provide substantially better conditions for germination than bare soil substrates during years when conditions for germination are favourable. What little positive effect the ash substrate has is likely to be swamped by climatic factors that influence seedling establishment and mortality. However, our results suggest that silvicultural treatments that create ash substrates could increase ponderosa pine germination during years when conditions for seedling establishment are marginal. Marginal conditions for ponderosa pine regeneration occur frequently simply because seed production is highly variable and often very low (McDonald, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008). Seed predation by small mammals can greatly reduce the amount of seed that is available to germinate (Vander Wall, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008). Seed predation by small mammals can greatly reduce the amount of seed that is available to germinate (Vander Wall, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008). Seed predation by small mammals can greatly reduce the amount of seed that is available to germinate (Vander Wall, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008). Seed predation by small mammals can greatly reduce the amount of seed that is available to germinate (Vander Wall, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008). Seed predation by small mammals can greatly reduce the amount of seed that is available to germinate (Vander Wall, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008). Seed predation by small mammals can greatly reduce the amount of seed that is available to germinate (Vander Wall, 1992; Krannitz and Duralia, 2004; Moghaddas et al., 2008).
A weather station within 2 km of both stands recorded weather data during the germination periods. In the spring of 2005, ponderosa pine germination was low and sugar pine germination was high. This period of high sugar pine germination was relatively wet and cold. Precipitation from January to June of 2005 was much higher (1260 mm) and soil temperature somewhat colder (5.6°C) than in the spring of 2007, which was relatively dry (653 mm) and warm (7.4°C). During the dry and warm year, ponderosa pine germination was high and sugar pine germination was low. This pattern in sugar pine is consistent with nursery studies of sugar pine germination requirements, where long cold stratification periods have been noted to greatly increase germination (Heit, 1968). It is unclear why ponderosa pine had greater germination frequency during the dryer and hotter year, considering moisture stress has been observed to reduce germination in P. ponderosa var. arizonica (Schubert, 1974). Site-specific information on phenology of soil moisture and temperature are needed to explain these differences. Staging harvests over multiple years or planting seedlings are both viable options that mitigate temporal variability in germination environments.

**Influence on light environment**

Prior to the gap-based approach most recently used in these stands, past selective harvests of individual trees from many size classes had achieved several of the traditional goals of multi-aged management: multiple age classes were initiated, productivity in terms of timber yield was relatively high, size structure was well balanced between size classes and periodic income was attained while avoiding costs of intermediate treatments. Yet this traditional approach was failing to achieve two objectives that have more recently become higher priorities throughout western US forests. Surface fuels had increased and pine regeneration, especially ponderosa pine, had greatly declined to the point where it was almost absent. Although the amount of light reaching the forest floor on average (12 per cent) prior to harvest was twice the average than in a nearby reserve stand, it was still not nearly enough to regenerate the local shade-intolerant species. This was in spite of significant reductions in stand-wide basal area (~40 per cent) during previous harvests. Past regeneration surveys following prior harvests indicate very little initiation of sugar pine regeneration and virtually no ponderosa pine regeneration. We therefore expect that adequate resource availability for pine regeneration will be restricted primarily to within the gaps created during these harvests. Even many of these gaps, which had an average of 40 per cent light availability within them, may be marginal for ponderosa pine recruitment. Inadequate light availability could be associated with gaps that are either too small or that have surrounding canopies that are too dense. Planting would likely improve recruitment through bypassing the germination and establishment phase of regeneration and allowing early seedling growth into higher light environments of the upper canopy. Survival of planted pine seedlings in this forest type was consistent across a gap-size gradient from 0.1 to 1.0 ha (York et al., 2007). However, survival in smaller gaps created in this study (~0.04 ha) could be considerably lower. Again, planting may be a viable option for addressing survival in small gaps. The cost-effectiveness of planting in multi-aged stands warrants further study to further evaluate the effectiveness of the gap-based approach to multi-aged management. Control of competing vegetation within gaps would also likely improve recruitment, as would the placement of gaps adjacent to particularly good specimen parent trees that are likely to produce more seed for natural regeneration.

**Synthesis and conclusions**

Many of the negative outcomes traditionally associated with multi-aged stands (Guldin, 1996) can be moderated or resolved by designing harvests and post-harvest treatments to specifically meet modern objectives. The creation of small gaps followed by burning within gaps in this study effectively addressed two of the major concerns of multi-aged stands in western North American forests – surface fuel loading and regeneration of shade-intolerant pine species. While this type of micro-management of small regeneration areas nested within multi-aged stands may seem counter to the concept of these systems being less intensive or ‘more natural’, they nonetheless are treatment alternatives for achieving what would otherwise be unachievable objectives using more traditional multi-aged approaches. Further, the 10-year re-entry cycle is similar to the known fire return intervals in these forests (Stephens and Collins, 2004) and therefore to an extent emulates disturbance frequency of the natural disturbance regime (sensu, Long, 2009).

The addition of fire after gap creation could be viewed as an additional step towards the emulation of a natural disturbance regime (Long, 2009). While the highly controlled nature of fires confined to piles within gaps does not represent the spatial heterogeneity that can be achieved with prescribed fires that cover larger areas, the gap-based approach also avoids the blunt and often unpredictable effects of stand-level prescribed fires (Hartsough et al., 2008). Where risk of loss of commercial timber value or the risk of fire escape is unacceptable (e.g. stands designated for timber production or areas adjacent to neighbouring landowners), this gap-based approach to harvesting and burning represents a viable alternative that retains the benefit of fire while avoiding many of its risks.

**Funding**

California Agricultural Experiment Station to J.J.B.

**Acknowledgements**

We acknowledge the field assistance provided by W. D. Rambeau, J. Wheeler and J. Restaino, who also reviewed an earlier version of the manuscript.
Conflict of interest statement

None declared.

References

Agee, J.K. and Skinner, C.N. 2005 Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211, 83–96.

Ansley, J.S. and Battles, J.J. 1998 Forest composition, structure, and change in an old growth mixed conifer forest in the northern Sierra Nevada. J. Torrey Bot. Soc. 125, 297–308.

Brown, J.K. 1974 Handbook for Inventorying Downed Woody Material. USDA Forest Service General Technical Report INT-197. Forest and Range Experiment Station, Ogden, UT.

Canham, C.D., Denslow, J.S., Platt, W.J., Runkle, J.R., Spies, T.A. and White, P.S. 1990 Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Can. J. For. Res. 20, 620–631.

Carlton, D. 2005 Fuels Management Analyst Plus. Fire Program Solutions, LLC/Accacia Services, Esticada, OR.

Collins, B.M., Stephens, S.L., Moghaddas, J.J. and Battles, J.J. 2010 Challenges and approaches in planning fuel treatments across fire-excluded forested landscapes. J. For. 108, 24–31.

Fisher, G.M. 1935 Comparative germination of tree species on various kinds of surface-soil material in the western white pine type. Ecology. 16, 606–611.

Fites-Kaufman, J., Rundel, P., Stephenson, N. and Weixelman, D.A. 2007 Montane and subalpine vegetation of the Sierra Nevada and Cascade ranges. In Terrestrial Vegetation of California. M. Barbour, T. Keeler-Wolf and A.A. Schoenherr (eds). University of California Press, Berkeley, CA, pp. 456–501.

Frazer, G.W., Trofymow, J.A. and Lertzman, K.P. 2000 Canopy openness and leaf area in chronosequences of coastal temperate rainforests. Can. J. For. Res. 30, 239–256.

Gray, A.N., Zald, H.S., Kern, R.A. and North, M. 2005 Stand conditions associated with tree regeneration in sierran mixed-conifer forests. For. Sci. 51, 198–210.

Guldin, J.M. 1996 The role of uneven-aged silviculture in the context of ecosystem management. West. J. Appl. For. 11, 4–12.

Hartsough, B.R., Abrams, S., Barbour, R.J., Drews, E.S., McIver, J.D., Moghaddas, J.J. et al. 2008 The economics of alternative fuel reduction treatments in western United States dry forests: Financial and policy implications from the National Fire and Fire Surrogate Study. For. Ecol. Manage. 10, 344–354.

Heit, C.E. 1968 Thirty-five years’ testing of tree and shrub seed. J. For. 66, 632–634.

Keeler, J.E. and Zedler, P.G. 2000 Life history evolution of pines. In Ecology and Biogeography of Pinus. D.M. Richardson (ed). Cambridge University Press, Cambridge.

Kinloch, B.B. and Scheuner, W.H. 1990 Pinus lambertiana Doug. In Silvics of North America Volume 1. Conifers. R.M. Burns and B.H. Honkala (eds). tech. coords. USDA Forest Service, Washington, DC. Agriculture Handbook 654.

Kobe, R.H. and Hogarth, L.J. 2007 Evaluation of irradiance metrics with respect to predicting sapling growth. Can. J. For. Res. 37, 1203–1213.

Kranzitz, P.G. and Duralia, T.E. 2004 Cone and seed production in Pinus ponderosa: a review. West. N. Am. Nat. 64, 208–218.

Laiho, O., Lähde, E. and Pukkala, T. 2011 Uneven- vs. even-aged management in Finnish boreal forests. Forestry. doi:10.1093/forestry/cpr032

Long, J.N. 2009 Emulating natural disturbance regimes as a basis for forest management: A North American view. For. Ecol. Manage. 257, 1868–1873.

Mathews, J.D. 1992 Silvicultural Systems. Oxford Science Publications, Oxford.

McDonald, P.M. 1992 Estimating seed crops of conifer and hardwood species. Can. J. For. Res. 22, 832–838.

Miller, J.D., Safford, H.D., Crimmins, M. and Thode, A.E. 2009 Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems. 12, 16–32.

Minore, D. 1979 Comparative Autecological Characteristics of Northwestern Tree Species: A Literature Review. Pacific Northwest Experiment Station. USDA Forest Service, Portland, OR, 56 pp.

Moghaddas, J.J., York, R.A. and Stephens, S.L. 2008 Initial response of conifer and California black oak seedlings following fuel reduction activities in a Sierra Nevada mixed conifer forest. For. Ecol. Manage. 255, 3141–3150.

North, M., Hurteau, M., Fiegner, R. and Barbour, M. 2005 Influence of fire and El Niño on tree recruitment varies by species in Sierran mixed conifer. For. Sci. 51, 187–197.

North, M., Stine, P., O’Hara, K., Zielinski, W. and Stephens, S. 2009 An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests. USDA Forest Service. PSW-GTR-220, pp. 1–49.

O’Hara, K.L., Hasenauer, H. and Kindermann, G. 2007 Sustainability in multi-aged stands: an analysis of long-term plenter systems. Forestry. 80, 163–181.

O’Hara, K.L. and Nagel, L.M. 2006 A functional comparison of productivity in even aged and multigated stands: a synthesis for pinus ponderosa. For. Sci. 52, 290–303.

Oliver, W.W. and Ryker, R.A. 1990 Pinus ponderosa Doug. ex Laws. Ponderosa Pine. In Silvics of North America. R.M. Burns and B.H. Honkala (eds). tech. coords. USDA Forest Service, Washington, DC. Agricultural Handbook 654.

Pierce, A.D. and Taylor, A.H. 2010 Competition and regeneration in quaking aspen – white fir (Populus tremuloides–Abies concolor) forests in the Northern Sierra Nevada, USA. J. Veg. Sci. 21, 507–519.

Pierce, K.B., Ohmann, J.L., Wimberly, M.C., Gregory, M.J. and Fried, J.S. 2009 Mapping wildland fuels and forest structure for land management: a comparison of nearest neighbor imputation and other methods. Can. J. For. Res. 39, 1901–1916.

Puetzmann, K.J., Koates, K.D. and Messier, C. 2009 A Critique of Silviculture: Managing for Complexity. Island Press, Washington, DC.

Reiner, A.L., Vaillant, N.M., Fites-Kaufman, J. and Dailey, S.N. 2009 Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada. For. Ecol. Manage. 258, 2363–2372.

Schmidt, D.A., Taylor, A.H. and Skinner, C.N. 2008 The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California. For. Ecol. Manage. 255, 3170–3184.
