



Spatial variation of fuel loading within varying aged stands of chaparral

Kellie A. Uyeda, Douglas A. Stow, John F. O'Leary, Ian T. Schmidt & Philip J. Riggan

Keywords

Adenostoma fasciculatum; Biomass accumulation; California chaparral; Chamise; Post-fire recovery; *Quercus berberidifolia*; Scrub oak; Shrub; Stand age; Vegetation type map; Wildfire

Nomenclature

Baldwin et al. (2012)

Received 24 February 2015

Accepted 14 October 2015

Co-ordinating Editor: Norbert Hölzel

Uyeda, K.A. (corresponding author, kellie.uyeda@gmail.com)^{1,2},

Stow, D.A. (stow@mail.sdsu.edu)¹,

O'Leary, J.F. (oleary@mail.sdsu.edu)¹,

Schmidt, I.T. (itssit@gmail.com)¹,

Riggan, P.J. (priggan@fs.fed.us)³

¹Department of Geography, San Diego State University, 5500 Campanile Drive, San Diego, CA, USA;

²Department of Geography, University of California, 1832 Ellison Hall, Santa Barbara, CA 93106-4060, USA;

³Pacific Southwest Research Station, United States Forest Service, 4955 Canyon Crest Drive, Riverside, CA 92507, USA

Abstract

Questions: How do stand-level biomass and percentage of dead material in chaparral vary as a function of stand age? How do the landscape properties of aggregation index and patch size vary in each of the dominant species groups as a function of stand age?

Location: Stands of 7-, 28- and 68-yr-old chaparral, San Diego County, CA, US.

Methods: We sampled and estimated above-ground biomass in 8 m × 8 m field plots. Each stand was classified into species groups using high-resolution imagery. After establishing coefficients for the average biomass per area for each species group and stand age using field data, we estimated biomass in 30 random plots in each stand age using the classified map. We also estimated biomass using pooled coefficients (average of the 28- and 68-yr-old biomass per area). We calculated landscape metrics in six 60 m × 60 m study sites for each stand age.

Results: While we found a statistically significant pattern of higher biomass in the older chaparral stands when using age-specific biomass coefficients, there was no statistical difference between the 28- and 68-yr-old stands using the more conservative pooled coefficients. Both approaches revealed a wide range in biomass in all age classes. We were not able to map dead biomass with sufficient accuracy to measure age-related differences, but no differences in the two older stands were obvious in the field. There were no significant differences in landscape metrics between the two older stands, and the differences observed in the younger stand might have been partially due to aspect differences.

Conclusions: Our approach of using a combination of field plots and classification of remote sensing imagery is a valuable method for enlarging the effective study area in chaparral, and allowed us to better measure how widely biomass varies across the study area. High spatial resolution measurements of fuel properties could help support more detailed models of fire behaviour.

Introduction

In southern California chaparral shrublands, wildfires typically occur as intense crown fires, with behaviour influenced by high temperatures, low humidity, high wind, terrain and biomass levels. The fires consume all above-ground biomass but the largest live stems in the thick stands of sclerophyllous shrubs. The first 3 to 4 yr following a fire are characterized by an abundance of herbaceous vegetation, after which time shrubs become dominant and return to pre-fire cover levels within 10 to 15 yr (Keeley et al. 1981; McMichael et al. 2004). While shrub cover returns to pre-fire levels fairly rapidly, the amount of total above-ground biomass continues to increase with time

(Riggan et al. 1988). The rate of this accumulation declines with time within the first two decades of recovery, but there appears to be positive net accumulation at least until an age of approximately 40 yr (Rundel & Parsons 1979; Black 1987). After 40 yr, vegetation biomass tends to reach a steady state (Black 1987). These patterns of biomass accumulation are important for understanding ecosystem productivity following a fire, which is closely related to the fuel available for future fires and ecological effects of fires (Riggan et al. 1988).

Although broad-scale patterns of fire frequency are not necessarily related to fuel age (Moritz et al. 2004; Keeley & Zedler 2009), fuel characteristics such as total fuel loading and percentage moisture are among the important factors

that determine fire spread success (Weise et al. 2005). The contribution of dead fuel is particularly important for fire spread since the low moisture levels of dead fuel may allow fire to spread through live fuels (Countryman & Dean 1979).

In a broad sense, the total amount of dead fuel increases with time as branches die back due to light limitation (Mahall & Wilson 1986), drought stress (Davis et al. 2002) or pathogens (Riggan et al. 1994), or as entire shrubs die during stand development (Schlesinger et al. 1982; Riggan et al. 1988). However, the proportion of dead fuel is highly variable. Even for a single species and over large areas, stand age is likely not the most important factor in determining the proportion of dead fuel (Paysen & Cohen 1990). Dead remnant stems from the last fire are also an important source of dead fuel. In young stands without high live biomass, these dead remnant stems may represent a high percentage of total biomass (Regelbrugge & Conard 1996). Large remnant stems, when burned, may not contribute greatly to stand ignitability or fire behaviour, but would contribute to overall energy release and some ecological fire effects, such as soil heating.

Since the time scales of biomass accumulation are so long, it is usually impossible to track a single stand through time. Instead, researchers typically take measurements from multiple stands to reconstruct a chronosequence of temporal change in fuel (e.g. Specht 1969; Black 1987). Due to the large areas commonly consumed by wildfires, stands that make up each age group are often composed of heterogeneous vegetation, soil types and terrain characteristics. Also, areas that remain unburned for long periods of time may fundamentally differ in their landscape characteristics from those that frequently burn or have recently burned.

Previous studies have found variability in chaparral biomass at fine spatial scales (Black 1987). Such variability could affect the characteristics of fire, although more data are needed to link fine-scale fire behaviour patterns to the broad scales of interest to fire managers (Hiers et al. 2009). One source of variation is due to the species composition of a given stand. *Adenostoma fasciculatum* (chamise), the most common chaparral shrub in California (Hanes 1971), has been relatively well studied in terms of shrub-scale fuel properties. It has fine, needle-like leaves, with a high proportion of small diameter stems (Countryman & Philpot 1970). It retains dead stems in the canopy, which contributes to increased fire intensity (Schwilk 2003). The percentage of dead biomass is highly variable even in stands of the same age, and might be related to site productivity (Countryman & Philpot 1970; Riggan et al. 1988). *A. fasciculatum* is commonly found on south-facing slopes (Hanes 1971). *Quercus berberidifolia* (scrub oak) is also often present in California chaparral, typically on north-facing slopes

(Hanes 1971). It has relatively broad leaves, and accumulates only low levels of standing dead biomass (Riggan et al. 1988). It has a comparatively lower proportion of small diameter stems (Riggan et al. 1988) and is usually taller, with higher fuel volume than *A. fasciculatum* (Green 1970). Regardless of this variation, fuel mapping efforts typically focus on relatively coarse groupings of fuel types rather than species-specific measurements (Arroyo et al. 2008). In addition to specific fuel mapping projects, fire managers have information such as previous fire perimeters, vegetation type and fire threat readily available for the entire state of California from the Fire and Resource Assessment Program (<http://frap.fire.ca.gov/>, accessed 10 Jul 2015).

The objective of this study is to measure the fine-scale changes in fuel properties that occur over long time periods as southern California chaparral ages. Understanding how fuel properties such as total and dead biomass and their spatial arrangement across the landscape change with age has the potential to improve fire modelling and inform fuel management policies.

We address the following research questions using detailed measurements of chaparral field plots and high-resolution species group mapping: (1) how do stand-level biomass and percentage of dead material vary as a function of stand age; and (2) how do the landscape properties of aggregation index and patch size vary in each of the dominant species groups as a function of stand age?

Methods

Study site

The site for this study is located near Kitchen Creek Road on southern Laguna Mountain in San Diego County, CA, US (Fig. 1). Chaparral there experiences a typical mediterranean-type climate with hot, dry summers and cool, wet winters. The soils are classified as being in the Bancas series, which are fine loamy, mixed, mesic and mollic haploxeralfs derived from quartz diorite and mica schist (<http://websoilsurvey.nrcs.usda.gov/>, accessed 19 Dec 2014). Average annual precipitation is 66 cm·yr⁻¹ (<http://www.prism.oregonstate.edu/>, accessed 4 Apr 2014). *Adenostoma fasciculatum*, a facultative seeder and *Quercus berberidifolia*, an obligate resprouter, are dominant species on the site, although *Arctostaphylos glandulosa* and *Ceanothus perplexans* (formerly *Ceanothus greggii* var. *perplexans*) are also commonly found. The general study location has previously served as the field site for a study of chaparral community development (Riggan et al. 1988).

The entire study area burned in 1944. Three strips were burned as part of an experimental burn in 1979, then additional areas were burned in the early 1980s, creating one burned area approximately 300 m north of another

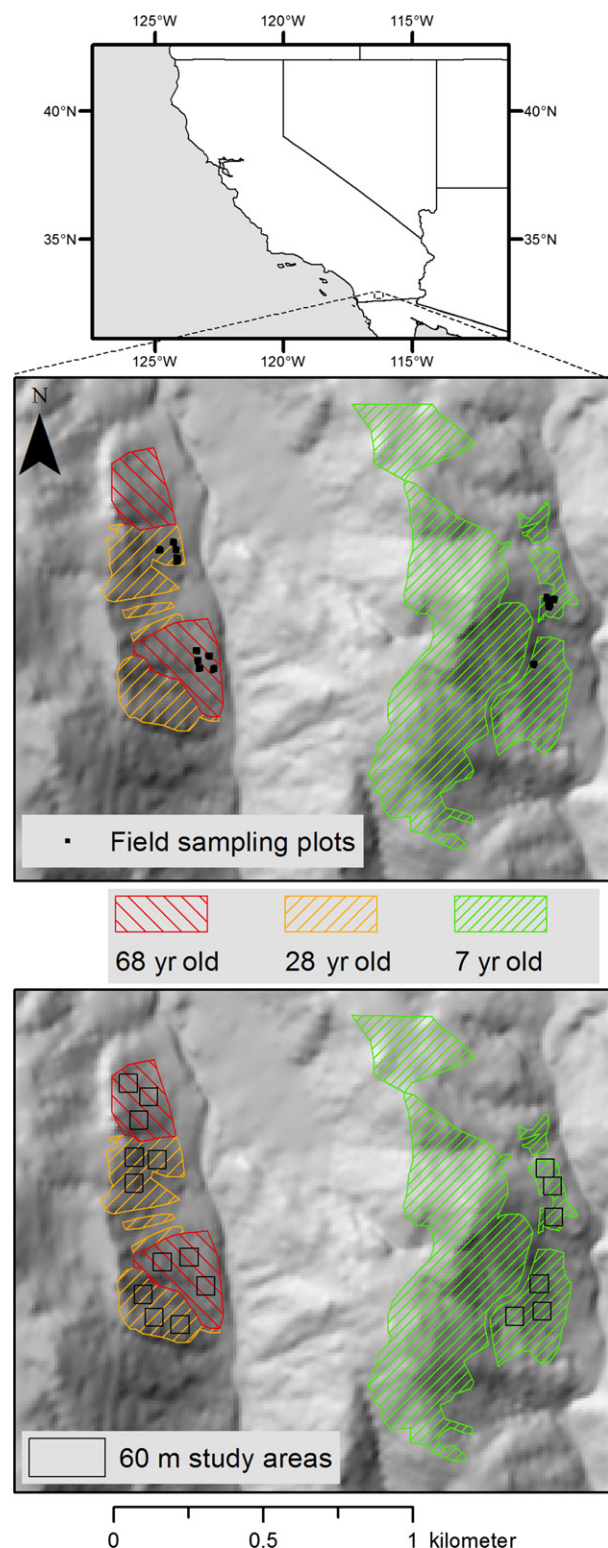


Fig. 1. Overview of field sites and 60 m × 60 m study areas at Kitchen Creek (western burn areas) and Long Canyon (eastern burn area). Fire perimeters at Kitchen Creek were digitized based on imagery collected in 1985.

burned area on a background of older vegetation in the study area, designated 'Kitchen Creek' (Dougherty & Riggan 1982; Riggan et al. 1988). In 2005, a prescribed burn was conducted on the nearby site called 'Long Canyon'. This created three stand ages (68 yr, approximately 28 and 7 yr) all within 1 km of one another at elevations ranging from 1430 to 1520 m a.s.l. While minimal differences in aspect exist between the two older, mostly east-facing sites, the 7-yr-old site is more southeast-facing.

Field methods

Figure 2 shows a flow chart with the processing steps used in this study. Five 64 m² (8 m × 8 m) plots encompassing the range of variability of the study area were selected from each of the three age classes for a total of 15 plots. Shrub cover in the two older areas was extremely dense, and we were only able to access the plots in a timely fashion because a trail was cut through the study area by a fire crew from the US Forest Service. All plots in the Kitchen Creek area were located within 40 m of this trail. Plot boundaries were recorded in the field using Trimble GeoXM handheld Global Positioning System (GPS) unit with a post-processed accuracy of 1 to 3 m. We measured all shrub stems 0.4 cm or more in diameter within the plots at 10 cm above the ground using digital calipers, and recorded the species of the stem and whether it was live, dead or charred. On irregularly shaped stems, we recorded the minimum and maximum stem diameters to determine the average stem diameter. Live stems were identified by the presence of green leaves, so stems that were mostly dead were still counted as live if green leaves were present.

We harvested live, dead and, for the 7-yr-old area, charred stems from the most abundant species (*A. fasciculatum*, *Q. berberidifolia*, *A. glandulosa*, *C. perplexans*) near the sampling plots to determine field weight and basal diameter. We typically sampled one species per day and selected one shrub per day to serve as a representative sample to estimate the ratio of dry to wet weights. This representative shrub was brought to the lab where we separated it into small (<0.5 cm), medium (0.5 cm to 2.0 cm) and large (>2.0 cm) diameter fractions. We weighed each size fraction and subsampled it to determine water content. Samples were dried to a constant mass in a drying oven at 100 °C. We determined the total shrub water content by applying the appropriate water content value to the biomass of each shrub fraction to calculate an average water content scaled by size fraction. This value was then applied to all shrubs sampled on that day. This sampling took place mostly in the autumn and early winter seasons from 2011–2013.

We calculated coefficients for the relationship of dry above-ground biomass (*AGB*) as a power function of stem

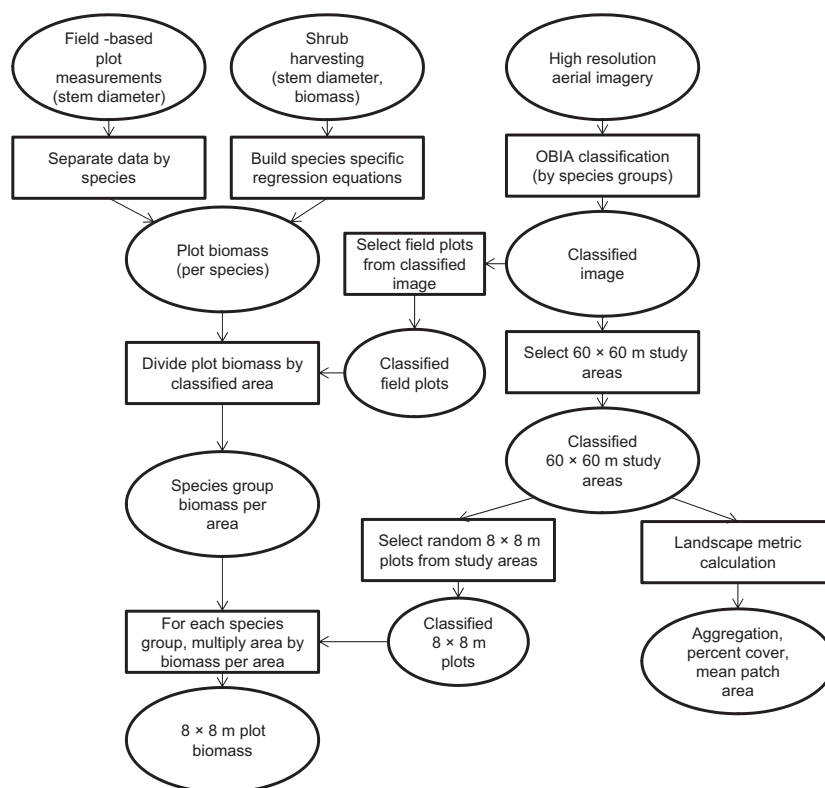


Fig. 2. Flowchart of field and remote sensing methods.

basal area (BA) with a bias correction applied (Baskerville 1972; Sprugel 1983):

$$\text{AGB} = B_0(\text{BA})^{B_1} e^{0.5s} \quad (1)$$

where s is the residual mean square, B_0 is the proportionality coefficient and B_1 is the scaling exponent.

In order to optimize time spent in the field, we generated species and age-specific equations for each species in the burned areas where they were most abundant. For example, *Q. berberidifolia* was only occasionally found in the 7-yr-old area, so we used the equation from the 28-yr-old area rather than generating a new equation. We also generated a generic equation for each age class using the pooled measurements across all species to provide an estimate for less abundant species. We calculated above-ground biomass for entirely dead shrubs that could not be identified by species using the generic dead shrub equation for the appropriate burn year. Charred stems were only occasionally found in the older stands, so we estimated charred biomass in these areas using half the value given by the appropriate equation for dead biomass.

Image classification

In order to efficiently characterize the fuel properties of each age class, we classified imagery from the 68- and

28-yr-old age classes of chaparral using colour (RGB) aerial imagery collected by Near Earth Observation Systems (NEOS) in Jun 2012 using a 21-megapixel digital camera. The imagery was geometrically corrected using control point based warping and mosaicked using nearest neighbour resampling to create a single image of the entire Kitchen Creek study area. The ground sample distance (GSD) of the corrected data set was 4 cm. In addition, the normalized difference vegetation index (NDVI) from May 2012 colour infrared (CIR) imagery having a nominal 50 cm GSD was also used for the classification. NDVI is calculated as the difference of near infrared and red digital number values divided by the sum of those values. While some of the 7-yr-old age class was covered by the NEOS imagery, the coverage was not sufficient to classify vegetation within the entire area. Thus, the 2012 50 cm CIR imagery was used as input to the image classification. NEOS imagery was used as a reference for training purposes.

The image-based classification system consisted of the categories broad-leaf shrubs, Af/Ag, sub-shrub, bare and dead categories. We aggregated the biomass measured in the field to those categories. The broad-leaf category mostly consisted of *Q. berberidifolia* and *C. perplexans*, although the less common species *Ceanothus leucodermis*, *Cercocarpus betuloides*, *Quercus agrifolia*, *Rhamnus ilicifolia*, *Rhus ovata*, *Rhus trilobata* and *Ribes indecorum* were also

included. The Af/Ag class included the species *A. fasciculatum* and *A. glandulosa*. We treated these species as a separate class since they featured a lower biomass per area than the other shrub species. The sub-shrub category was mostly composed of *Salvia apiana*, but also included small amounts of *Trichostema lanatum*, *Keckiella ternata*, *Hazardia squarrosa* and *Eriogonum fasciculatum*. The bare category was mostly composed of granite outcroppings in the 28- and 68-yr-old areas, and a combination of granite outcroppings and bare ground in the 7-yr-old area. The dead category included only shrubs that were entirely dead. Dead biomass attached to living shrubs was included within the appropriate species group. We were unable to classify dead cover in the 7-yr-old area due to the relatively coarse resolution of the imagery and small quantity of dead material in this area. We collected calibration/validation samples from 1 m × 1 m plots in the Kitchen Creek study area (68- and 28-yr-old vegetation) along the trail using the Trimble GeoXM GPS unit. Eighteen of the plots were used to train the classifier, and 42 were used for validation.

We used eCognition, an object-based image analysis (OBIA) software package, for image-based classification of vegetation types (eCognition Developer 8.9, <http://www.ecognition.com/>). OBIA segments an image into groups of adjacent pixels (objects) and then assigns these objects to the categories of the classification scheme based on a set of user-defined rules. We used an iterative segmentation/classification approach, re-segmenting several times to create objects of the appropriate size for the class of interest. A multi-resolution segmentation algorithm with scale parameters of 10 and 15 was implemented, as well as the chessboard segmentation algorithm with object sizes of 1 and 10. The multi-resolution segmentation algorithm works by iteratively merging adjacent pixels based on criteria of spectral and shape homogeneity, and the scale parameter modifies the size of the final image objects. The chessboard segmentation algorithm simply divides the image into equally sized square objects. After each round of segmentation, we used properties such as texture, brightness, colour, adjacency and NDVI to classify the objects in the class of interest, then merged the unclassified objects so they could be re-segmented with appropriate parameters for the next class of interest. Although we made minor manual corrections to the vegetation type maps in the primary study area, the accuracy assessment was based on the uncorrected classification results.

Landscape analysis

Vegetation cover percentages of each field plot were extracted from the image classification product. We calculated biomass per m² using biomass measured in the field and species category cover taken from imagery

classification. We used the average biomass per m² of the two plots from each age and species category with the highest field measured biomass for a given species category. Since the plots were composed of a mixture of species, samples of some plots were not representative of the species category of interest. In order to reduce the error associated with these plots, we based our calculation on only the plots in which the species category of interest was abundant. In order to provide a more cautious estimate of biomass, we also calculated the average biomass per m² for the combined 68- and 28-yr-old areas. We did not include the 7-yr-old area in this calculation because these values were much lower than those found in the older burn areas.

There were not enough areas of sub-shrub in the 68-yr-old plots to calculate an average, so the values for these plots were estimated from the 28-yr-old plots. Dead biomass per area values fluctuate so widely that it was not possible to calculate realistic values with the procedure used for the rest of the species groups. We simply used a value of 2 kg·m⁻² to approximate dead vegetation. This approximation is based on half the value calculated for the combined 68- and 28-yr-old Af/Ag coefficient.

We selected six 60 m × 60 m study areas within each age class for a total of 18 large study areas. We selected this size because it was the largest area that would fit in the burn perimeters of the 7-yr-old area. We clustered the study areas into three northern and three southern study areas, each separated by at least 200 m (Fig. 1). The aspect of the 60 m × 60 m study areas, based on a 10 m spatial resolution digital elevation model, is shown in Appendix S1. In each of these study areas, we randomly selected five 8 m × 8 m plots for a total of 30 plots per burn age (90 plots total).

The landscape properties of aggregation index and patch size were derived from vegetation-class patches from the 18 large study areas using the software program Fragstats (v 4.1, <http://www.umass.edu/landeco/research/fragstats/fragstats.html>). The aggregation index is calculated by dividing the cell adjacencies of a given class by the total number of possible cell adjacencies for that class. It is given as a percentage, such that a given class clumped in a single, compact patch would have a value near 100. Patch size for each species group was calculated using the area-weighted patch mean size, in which each patch is weighted by its proportional area representation. We also examined species composition by calculating the percentage cover of each species group. Since the vegetation map of the 7-yr-old age class was produced using 0.5 m imagery, we reduced the resolution of the 68- and 28-yr-old age classes (originally 4 cm) to match this lower resolution of 50 cm. In order to more closely examine the differences in the 68- and 28-yr-old age classes, we also calculated the same met-

rics using the original resolution (4 cm) vegetation classification.

Data analysis

The first research question – how does stand-level biomass vary as a function of stand age? – was addressed using the classified map of biomass. We calculated the total biomass using the age-specific coefficients determined previously. To determine if differences in biomass were robust to possible error in the age-specific coefficients, we also calculated an estimate of biomass using the averaged coefficients for the 68- and 28-yr-old age classes. We tested for biomass differences in the three age classes with one-way ANOVA ($n = 30$).

We addressed the second research question – how do the landscape properties of aggregation index and patch size vary in each of the dominant species groups as a function of stand age? – using the landscape scale metrics from

the 60 m $\times$ 60 m study areas. We compared the difference in these metrics in the three age classes with one-way ANOVA ($n = 6$). We compared the landscape metrics for the original resolution vegetation classification based on two age classes using a series of t -tests ($n = 6$).

Results

Stand-level biomass

Regressions of biomass as a function of basal area for the four chaparral species are presented in Fig. 3, and regression coefficients are shown in Appendix S2. The coefficient of determination (R^2) values for the biomass equations ranged from 0.82 to 0.97. The R^2 values for dead biomass were somewhat lower, and ranged from 0.65 to 0.96. The covariation between biomass and basal area was highest in 68-yr-old *Q. berberidifolia* and lowest in 7-yr-old *A. fasciculatum*. We were able to use a species-specific equation to calculate shrub biomass for at least 90% of the total basal

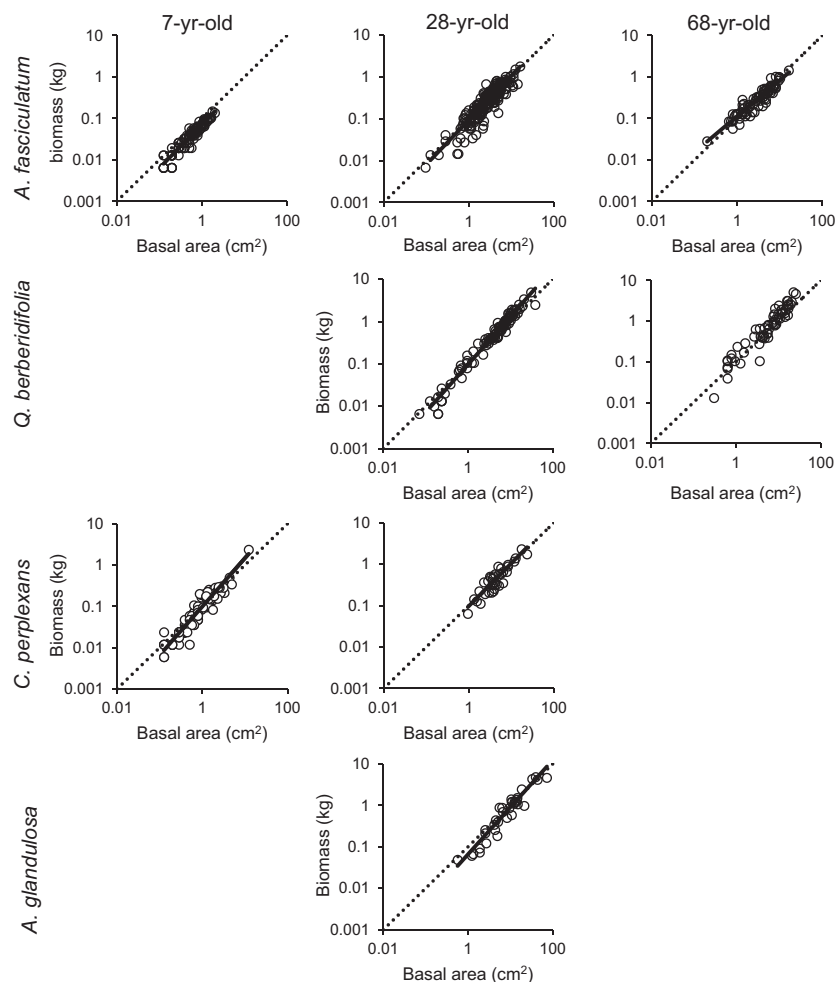


Fig. 3. Regressions of biomass as a function of basal area. The dotted line is the 10:1 line.

area present in each plot. We made every effort to sample shrubs from the full range of basal area values found in the field plots, but it was not always possible to locate large enough shrubs for the destructive sampling. A maximum of 4% (and usually much less) of all stems in the field plots were so large as to require an extrapolation of the regression equation to estimate biomass.

Biomass measurements from the field survey ranged from 7.5 kg·m⁻² in one of the oldest plots to 1.1 kg·m⁻² in one of the youngest plots (Appendix S3). The highest biomass values were found in the 68-yr-old stand, particularly in plots dominated by *Q. berberidifolia*. Despite these much higher values in the oldest plots, there was considerable overlap in the total biomass values in the 68- and 28-yr-old plots. Total biomass values were much lower in the 7-yr-old plots, as expected. Charred stems were found only occasionally in the older areas, but were abundant in the 7-yr-old area. Charred stem biomass ranged from about one-third to nearly equivalent to the amount of post-fire growth in these plots, although the regression relationship for calculating charred stem biomass exhibited a high degree of scatter, meaning that actual values of charred biomass may vary substantially from what we estimated.

The percentage of dead biomass varied substantially, but was generally higher in *A. fasciculatum* than other species, and overall much lower in the 7-yr-old area. Since partially dead stems were categorized as 'live' if green leaves were still present, these values represent the lower bound of percentage dead biomass. Biomass from entirely dead shrubs was also highly variable and almost completely absent in the 7-yr-old area.

The image classification product of species groups was assessed to have an overall accuracy of 71% (Table 1), based on reference data from the 1 m × 1 m field-based validation sample plots. Accuracy was higher in the more abundant categories of broad-leaf and Af/Ag, and particularly low in the dead biomass category.

Estimated biomass per area ranged from 6.2 kg·m⁻² in the oldest age class of broad-leaf vegetation to 0.4 kg·m⁻²

in the youngest age class of sub-shrub vegetation (Table 2). The biomass per area coefficients provided a good approximation of the two major categories of shrub species (Af/Ag and broad-leaf) and of overall biomass (Fig. 4a–c). The predicted Af/Ag biomass values based on the mapped cover tended to yield a closer agreement with the field-measured plot biomass values, while the broad-leaf and the combined total calculations were more variable.

We found a significant difference in mean biomass in the three age classes when using age-specific biomass coefficients ($F_{2,87} = 326$, $P < 0.001$), and the post-hoc Tukey test revealed that all three means were significantly different (Table 3, Fig. 5). The calculated biomass values showed a clear trend of accumulation through time (Fig. 5). However, the differences between age classes were not as clear when using the biomass values calculated using pooled coefficients (average of 28- and 68-yr-old areas). Although the overall ANOVA was significant ($F_{2,87} = 243$, $P < 0.001$), the post-hoc Tukey test revealed that the 28- and 68-yr-old areas were not significantly different (Table 3, Fig. 5). An overall trend of increasing biomass through time was evident, but when using these pooled coefficients, the difference between the 68- and 28-yr-old areas was not significant (Fig. 5). Both the results from the age-specific and pooled coefficients revealed a

Table 2. Above-ground biomass per unit area based on classification.

Veg type	Age class	kg·m ⁻²
Broad-leaf	68	6.2
Broad-leaf	28	4.2
Broad-leaf	7	2.4
Broad-leaf	68/28	5.2
Af/Ag	68	4.3
Af/Ag	28	3.6
Af/Ag	7	1.4
Af/Ag	68/28	4
Sub-shrub	68/28	1.5
Sub-shrub	7	0.4

Table 1. Error matrix from field-based accuracy assessment of the classified high spatial resolution map.

		Field classification						User accuracy
		Af/Ag	Bare	Broad-leaf	Dead	Sub-shrub	Total	
Remote sensing classification	Af/Ag	10	1	4	0	0	15	0.67
	Bare	0	2	0	0	1	3	0.67
	Broad-leaf	3	0	17	2	0	22	0.77
	Dead	1	0	0	0	0	1	0.00
	Sub-shrub	0	0	0	0	1	1	1.00
	Total	14	3	21	2	2	42	
Producer accuracy		0.71	0.67	0.81	0.00	0.50		Overall accuracy 0.71

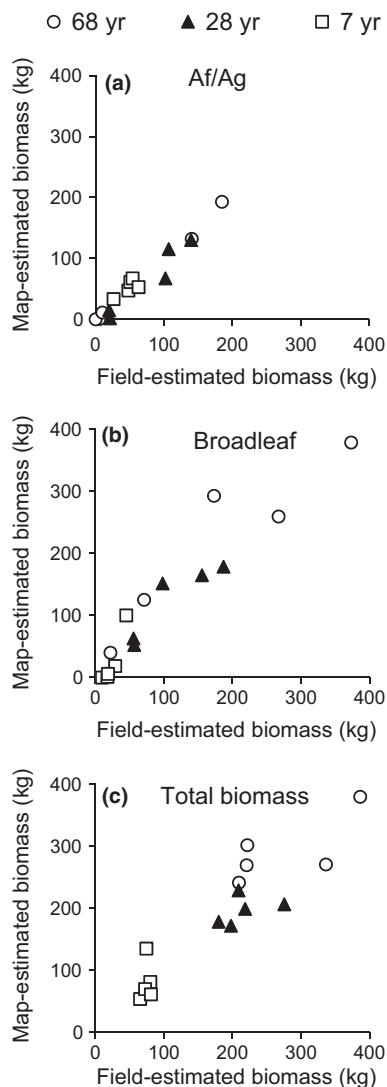


Fig. 4. Field-estimated biomass vs biomass estimated using age-specific biomass coefficients in each field plot for (a) Af/Ag, (b) broad-leaf, and (c) total biomass. The dotted line is the 1:1 line.

Table 3. Mean, range and ANOVA results for stand-level biomass comparisons using age-specific and pooled biomass coefficients. *df* = 2,87, *n* = 30

	7 yr	28 yr	68 yr	<i>F</i>	<i>P</i>
Age-specific					
Mean ($\text{kg}\cdot\text{m}^{-2}$)	1.3	3.4	5.1	326	<0.001
range	0.5–2.2	1.6–4.0	3.8–6.0		
Pooled					
Mean ($\text{kg}\cdot\text{m}^{-2}$)	1.3	4.0	4.4	243	<0.001
range	0.5–2.2	1.9–4.9	3.5–5.1		

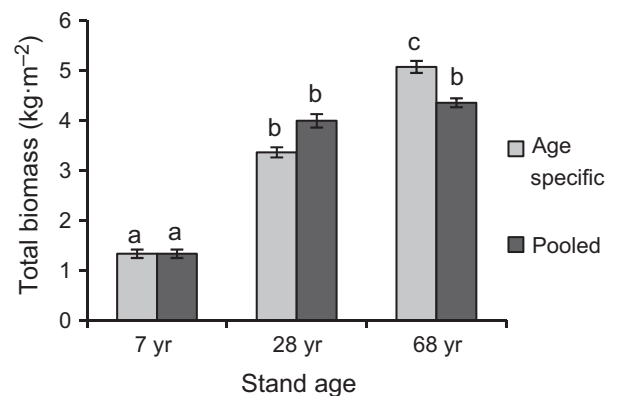


Fig. 5. Total biomass means using age-specific biomass coefficients and pooled biomass coefficients. Error bars indicate SE and letters indicate post-hoc Tukey tests. Bars with different letters are significantly different ($P < 0.05$).

wide range in biomass values for each stand age calculated for the 30 sampling plots (Table 3).

Landscape properties

The general trend of average percentage cover in the 60 m $\times$ 60 m study areas within each burn area indicates that broad-leaf percentage cover was higher in the older areas, sub-shrub cover was lower, and bare was not different (Fig. 6). Af/Ag cover was higher in the 28- than 7-yr-old area, and was similar in the 28- and 68-yr-old areas. However, closer inspection of the associated ANOVA results indicated that while there was a significant cover difference among several of the vegetation classes in each age class (e.g. broad-leaf, $F_{2,15} = 10.2$, $P = 0.0016$), post-hoc Tukey tests revealed that only the youngest age class was significantly different from the two older age classes (Table 4, Fig. 7a). The post-hoc Tukey tests showed the same pattern for the Af/Ag category and in the sub-shrub category, only the youngest and oldest age classes were significantly different (Fig. 7a).

In general across stand ages, the aggregation index (landscape pattern metric) is higher (more aggregated) in the broad-leaf and Af/Ag classes, and lower (more dispersed) for the sub-shrub and bare categories. Within the three age classes, only in the Af/Ag and sub-shrub categories are there significant differences in aggregation index with age (Af/Ag $F_{2,15} = 6.8$, $P = 0.0079$, sub-shrub $F_{2,15} = 6.9$, $P = 0.0077$; Table 4). Post-hoc Tukey tests show that in the Af/Ag category, only the 7- and 28-yr-old age classes are significantly different from one another, and in the sub-shrub category, only the 7- and 68-yr-old age classes are significantly different (Fig. 7b).

Area-weighted patch mean area is higher for the older age classes in the broad-leaf category, with only the differ-

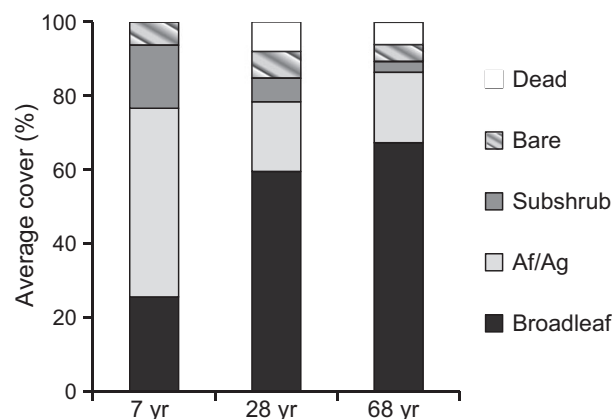


Fig. 6. Average percentage cover in the three age classes. Note that dead cover could not be estimated in the 7-yr-old age class.

ence between the youngest and oldest age class being significant ($F_{2,15} = 8.0$, $P = 0.0042$; Table 4). Patch mean area was lower in the youngest age class in the Af/Ag category, and the youngest area is significantly different than the two older areas ($F_{2,15} = 15.8$, $P = 0.0002$; Fig. 7c).

The series of t -tests of landscape metrics generated from the higher resolution (4 cm) classified imagery comparing the two older age classes indicate that the only significantly different classification/landscape metric combination is percentage cover of sub-shrub, which is higher for the 28-yr-old area ($df = 9.561$, $P = 0.009$; Table 5).

Discussion

Stand-level biomass

We could not make statistical inferences regarding the overall stand composition based on the field data. This was due to the sampling of plots that represented the range of variability found in our study area rather than random plots. We instead presented general observations about the

species composition and overall biomass present in the field plots. For this reason, we did not present averages or estimates of error associated with plot biomass values.

We found a high degree of variability in biomass in the study area due to species composition and stand age. Older stands had higher levels of biomass per area, and coefficients of the tall, dense species that make up the broad-leaf category were highest, followed by the more sparse Af/Ag category species, and finally by the much smaller sub-shrub species category. The regression equations calculated in this study were similar to those calculated in a previous study of the same area for the corresponding species and age (Riggan et al. 1988). The resulting biomass per area values were higher for each age than found by Riggan et al. (1988), but similar to those found in other studies within southern California (Black 1987; Riggan et al. 1988). Although the exact biomass per area coefficient values is not necessarily applicable to areas outside of this field site, these values provide valuable field data to more accurately map and estimate stand-level biomass across the study area. The high spatial resolution of the mapping effort allowed non-shrub cover (such as large rock outcrops) to be efficiently removed from the estimates of biomass per area. This means that caution must be used when applying the biomass coefficients from this study to mapping efforts based on lower resolution imagery, in which rock outcrops might not be reliably separated from shrub cover. Field-based biomass sampling is often too time consuming and logistically difficult to be conducted over large study areas (Lu 2006). Using remotely sensed imagery allows for biomass estimation over of much larger areas in an efficient manner. Our approach of using high spatial resolution imagery with object-based methods is reasonably successful for mapping fine-scale variation in species composition. Considering all the potential sources of error and uncertainty due to geolocation accuracy, field measurement error and other possible sources, it is promising

Table 4. ANOVA results for class metrics for the classified standardized resolution (0.5 m) data set. Bold P -values indicate significant results ($P \leq 0.01$). $df = 2,15$, $n = 6$.

Class	Metric	Mean 7-yr-old	Mean 28-yr-old	Mean 68-yr-old	F	P
Broad-leaf	Aggregation	83	86	89	3.0	0.0816
Af/Ag	Aggregation	81	65	70	6.8	0.0079
Sub-shrub	Aggregation	53	39	31	6.9	0.0077
Bare	Aggregation	44	63	53	3.8	0.0477
Broad-leaf	% of landscape	26	60	67	10.2	0.0016
Af/Ag	% of landscape	51	19	19	13.9	0.0004
Sub-shrub	% of landscape	17	6	3	6.7	0.0083
Bare	% of landscape	6	7	5	0.9	0.4315
Broad-leaf	Mean patch area (m^2)	321	1514	2155	8.0	0.0042
Af/Ag	Mean patch area (m^2)	1293	173	127	15.8	0.0002
Sub-shrub	Mean patch area (m^2)	79	5	3	4.1	0.0378
Bare	Mean patch area (m^2)	6	20	10	1.8	0.2059

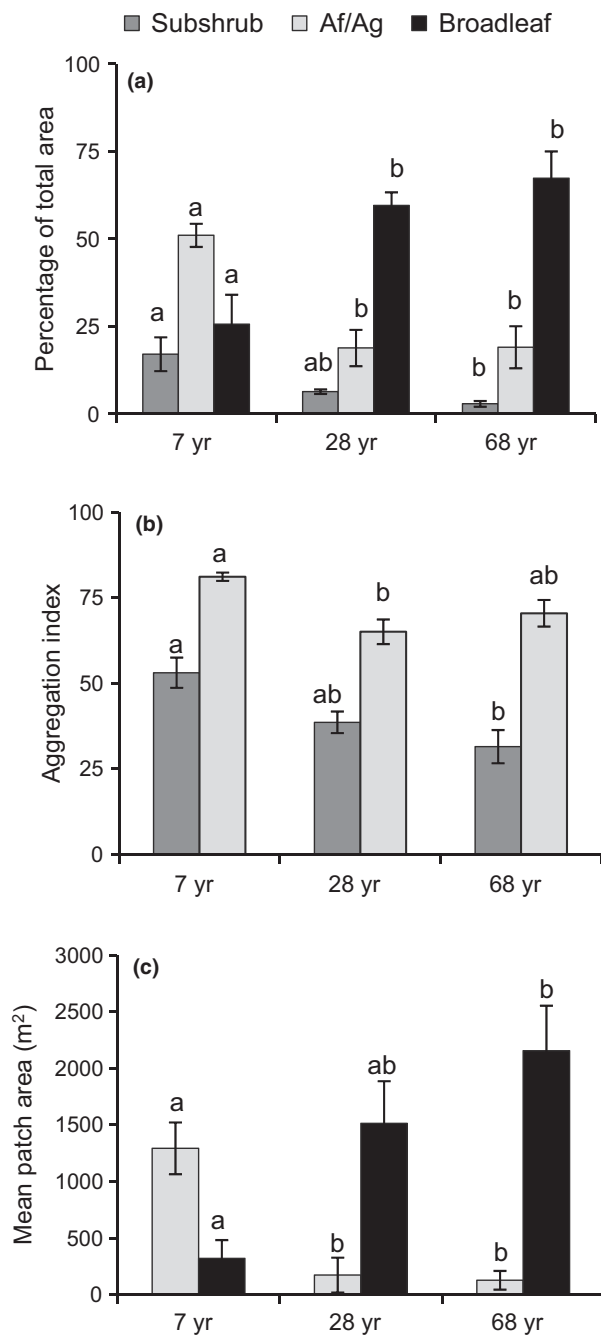


Fig. 7. (a–c) Mean and SE of significantly different age classes for the: (a) percentage of total area for sub-shrub, Af/Ag and broad-leaf categories, (b) aggregation index for Af/Ag and broad-leaf categories, and (c) mean patch area for Af/Ag and broad-leaf categories from the standardized resolution (0.5 m) data set. Letters indicate post-hoc Tukey comparisons. Bars with different letters are significantly different ($P \leq 0.05$).

that coefficients based on just two plots per stand age and species category yield such close agreement between field-estimated and map-estimated biomass. Mapping success at the species category level (and by extension, biomass)

could likely be further improved by using high spatial resolution colour infrared imagery.

It is more challenging to derive reliable maps of dead biomass based on image-based classification. This is partly due to the tendency of dead biomass to be located beneath plant canopies composed mostly of live biomass, either as dead stems within a single shrub or as an entirely dead shrub surrounded by live shrubs. This means that although dead biomass is often spread uniformly throughout stands of chaparral, it is only occasionally visible from above (which would allow it to be measured through aerial imagery). These small patches of dead biomass are not representative of the total dead biomass found in an area and make it more difficult to derive a relationship for biomass per unit area.

We calculated stand-level biomass in two ways to provide a more cautious estimate for the older sites. While results for the age-specific coefficients show a substantially higher biomass for the 68-yr-old areas, the results from the pooled coefficients indicate that the difference is not statistically significant. It is possible that if the 68-yr-old area had substantially more broad-leaf cover than the 28-yr-old area, the broad-leaf coefficient (higher than the Af/Ag coefficient in both the age-specific and pooled calculations) might have resulted in a higher biomass value in both calculations. However, it appears that differences are not that dramatic. Regardless of whether biomass continues to accumulate, it is clear that biomass levels remained high in the oldest stand of chaparral, consistent with the findings of previous studies (Specht 1969; Black 1987). Unsurprisingly, there was a large difference in biomass between the 7-yr-old and 28-yr-old stands. Shrub growth is rapid during this early phase of post-fire recovery and shrubs quickly expand in both cover and stature (Rundel & Parsons 1979; Keeley & Keeley 1981). While there were site differences between the 7-yr-old site and the older sites, the measurements of biomass per unit area for each species were based on areas in which each species is dominant.

Although it is still uncertain whether or not biomass continues to appreciably accumulate at older stand ages, the high number of plots examined through the scaling approach revealed a wide range of biomass values within a single age class. It is noteworthy that biomass varied so widely at the plot level (8 m $\times$ 8 m) within a relatively constrained spatial extent in an even-aged stand. This fine-scale spatial variation is typically difficult to map and might be important in understanding fire behaviour (Keane et al. 2001).

The scaling approach used in this study is based on two separate relationships, which has advantages and disadvantages. The final biomass values depend on both the stem-to-biomass regression relationship and the field-measured biomass-to-mapped cover category relationship. The

Table 5. *t*-test results from comparison of class metrics for classification of original resolution (4 cm) imagery from 68- and 28 yr-old sites. Bold *P*-value indicates significant results ($P \leq 0.01$). $n = 6$.

Class	Metric	Mean 28-yr-old	Mean 68-yr-old	<i>df</i>	<i>P</i>
Broad-leaf	Aggregation	98	99	6.091	0.419
Af/Ag	Aggregation	95	96	10.000	0.266
Sub-shrub	Aggregation	88	87	9.505	0.697
Bare	Aggregation	95	93	6.670	0.182
Dead	Aggregation	88	89	9.992	0.935
Broad-leaf	% of landscape	60	68	7.255	0.389
Af/Ag	% of landscape	19	19	9.783	0.982
Sub-shrub	% of landscape	6	3	9.561	0.009
Bare	% of landscape	7	5	9.930	0.084
Dead	% of landscape	8	6	9.108	0.228
Broad-leaf	Mean patch area (m ²)	1477	2105	9.850	0.269
Af/Ag	Mean patch area (m ²)	168	147	8.814	0.910
Sub-shrub	Mean patch area (m ²)	4	5	6.338	0.922
Bare	Mean patch area (m ²)	19	10	7.250	0.297
Dead	Mean patch area (m ²)	3	3	9.848	0.852

benefit of this approach is that it allowed for estimates over a much larger study area than could be adequately achieved using field sampling alone. However, there is an increased potential for error to propagate through the calculations. Still, the high degree of fine-scale variation observed in this study indicates that it was worthwhile to extrapolate the results across a larger area through this scaling approach at the cost of some degree of accuracy.

Landscape properties

Although landscape properties between the 28- and 68-yr-old areas are not substantially different, several significantly different relations were identified between the 7-yr-old site and the older sites. Broad-leaf cover and patch size were larger, while Af/Ag cover and patch size were smaller in the older age classes. Sub-shrub cover was also lower in the older age classes. While some of these differences might be due to age, it was difficult to make definitive comparisons in landscape properties between the 7-yr-old site and the older sites due to the slightly different aspect of the younger stand (more southeast-facing, compared to the more directly east-facing older sites). Another potential issue with these landscape-level comparisons was that the original classification of the youngest age site was based on a different (and lower resolution) imagery source than the older age classes. While we reduced the spatial resolution of the older age classes to make the results more comparable, it is possible that the results would be different had we been able to use high spatial resolution imagery for the entire study area. In particular, we likely would have been able to more accurately classify the small (but abundant) patches of bare ground observed during our field sampling in the youngest age class. The minimum spatial resolution required to detect a given feature on the ground is

generally considered to be one-half the diameter of that feature (Jensen 2005), and many bare patches observed in the field were smaller than 1 m in diameter. However, the overall trends we observed through the analysis of image-derived landscape properties seem consistent with observations in the field.

It is also important that almost no significant differences in the landscape properties of the 28- and 68-yr-old stands were identified, even when the high spatial resolution classification results were compared. Other than a small difference in sub-shrub cover, there were no differences in aggregation, percentage of landscape or patch size in these two older age classes. Although we were unable to confidently relate field measurements of dead biomass to classified dead biomass cover, it is still noteworthy that there was no significant difference in the landscape-level properties of dead biomass in the two older age classes. A high level of dead biomass in the oldest stand could indicate age-related die back, as observed by Hanes (1971). However, we observed no such age-related shrub die back in the older age classes, consistent with the findings of Keeley (1992).

Conclusion

While it is unclear whether there was a net accumulation in stand biomass from the age of 28 to 68 yr, there was little difference in the spatial arrangement of species groups in the two age groups. Biomass per unit area for each species was much lower in the 7-yr-old stand compared to the two older stands, and it seems reasonable to expect that for a given species, the trend towards higher biomass with increasing age reflects the process of post-fire shrub recovery. Due to the difference in aspect in the youngest stand, it was more difficult to determine if the differences in total biomass and landscape properties represented an age-

related trend. In all age classes, we found a wide range of biomass values, indicating a high degree of spatial variability within chaparral. It was difficult to map dead biomass, although simply knowing the species distribution could help inform estimates of dead biomass, as *A. fasciculatum* is known to retain dead stems (Schwilk 2003). Dead fuel loading is a significant attribute for modelling fire behaviour, so improved mapping of dead biomass is an important area for future research.

Although our field sampling was somewhat limited due to the physically difficult and time consuming nature of the measurements in barely penetrable mature chaparral shrublands, we were able to extrapolate our field sample across the entire study area through the use of high spatial resolution imagery and OBIA classification of vegetation types. Our approach of combining detailed field measurements with remotely sensed classification of dominant species groups to map the spatial arrangement of fuels in chaparral is a valuable method for characterizing biomass accumulation. An increased understanding of patterns of biomass accumulation could improve the accuracy of fuel mapping, which is important to fire management. Fuel maps are used for many purposes before and during wildfires, including planning fuel reduction treatments and modelling fire behaviour. Fire behaviour modelling relies on coarse-scale fuel models that do not take into account biomass accumulation through time or the wide range in biomass often present within a single stand (Riggan et al. 2010). Understanding biomass accumulation over a wide range of temporal and spatial scales could help to improve the inputs to fire behaviour models, increasing the accuracy of the predicted behaviour.

Acknowledgements

We thank J. Truett, T. Hayes and J. Kraling from the USFS for arranging for site access. We also thank D. Rachels, C. Riggan, A. Brown, F. Uyeda, J. Jesu, B. Lo, B. Corcoran, D. Smith and Y. Granovskaya for assistance in the field. Funding for this project was provided by the USDA Forest Service through American Recovery and Reinvestment Act Agreement No. 10-JV-11279701-10: Airborne remote sensing to enable hazardous fuels reduction, forest health protection, rehabilitation and hazard mitigation activities on federal lands.

References

- Arroyo, L., Pascual, C. & Manzanera, J. 2008. Fire models and methods to map fuel types: the role of remote sensing. *Forest Ecology and Management* 256: 1239–1252.
- Baldwin, B.G., Goldman, D.H., Keil, D.J., Patterson, R., Rosatti, T.J. & Wilken, D.H. 2012. *The Jepson manual: vascular plants of California*. University of California Press, Berkeley, CA, US.
- Baskerville, G. 1972. Use of logarithmic regression in the estimation of plant biomass. *Canadian Journal of Forest Research* 2: 49–53.
- Black, C.H. 1987. Biomass, nitrogen, and phosphorus accumulation over a southern California fire cycle chronosequence. In: Tenhunen, J.D., Catarino, F.M., Lange, O.L. & Oechel, W.C. (eds.) *Plant response to stress – functional analysis in mediterranean ecosystems*, pp. 445–458. Springer, Berlin, DE.
- Countryman, C.M. & Dean, W.A. 1979. *Measuring moisture content in living chaparral: a field user's manual*. Berkeley, CA, Gen. Tech. Rep. PSW-36. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 1982, Berkeley, CA, US.
- Countryman, C.M. & Philpot, C.W. 1970. *Physical characteristics of chamise as a wildland fuel*. Research Paper PSW-66, Pacific Southwest Forest & Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, CA, US.
- Davis, S., Ewers, F., Sperry, J., Portwood, K.A., Crocker, M.C. & Adams, G.C. 2002. Shoot dieback during prolonged drought in *Ceanothus* (Rhamnaceae) chaparral of California: a possible case of hydraulic failure. *American Journal of Botany* 89: 820–828.
- Dougherty, R. & Riggan, P.J. 1982. Operational use of prescribed fire in Southern California chaparral. In: Conrad, C.E. & Oechel, W.C. (eds.), *Proceedings of the symposium on dynamics and management of Mediterranean-type ecosystems*, pp. 502–510. Gen. Tech. Rep PSW-58, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, CA, US.
- Green, L.R. 1970. *An experimental prescribed burn to reduce fuel hazard in chaparral*. USDA Forest Service Research Note PSW-216, Berkeley, CA, US.
- Hanes, T.L. 1971. Succession after fire in the chaparral of southern California. *Ecological Monographs* 41: 27–52.
- Hiers, J.K., O'Brien, J.J., Mitchell, R.J., Grego, J.M. & Loudermilk, E.L. 2009. The wildland fuel cell concept: an approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. *International Journal of Wildland Fire* 18: 315.
- Jensen, J.R. 2005. *Introductory digital image processing: a remote sensing perspective*. Pearson Prentice Hall, Upper Saddle River, NJ, US.
- Keane, R.E., Burgan, R. & van Wageningen, J. 2001. Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire* 10: 301–319.
- Keeley, J.E. 1992. Demographic structure of California chaparral in the long-term absence of fire. *Journal of Vegetation Science* 3: 79–90.
- Keeley, J.E. & Keeley, S.C. 1981. Post-fire regeneration of southern California chaparral. *American Journal of Botany* 68: 524.

- Keeley, J.E. & Zedler, P.H. 2009. Large, high-intensity fire events in southern California shrublands: debunking the fine-grain age patch model. *Ecological Applications* 19: 69–94.
- Keeley, S.C., Keeley, J.E., Hutchinson, S. & Johnson, A. 1981. Postfire succession of the herbaceous flora in southern California chaparral. *Ecology* 62: 1608–1621.
- Lu, D. 2006. The potential and challenge of remote sensing based biomass estimation. *International Journal of Remote Sensing* 27: 1297–1328.
- Mahall, B.E. & Wilson, C.S. 1986. Environmental induction and physiological consequences of natural pruning in the chaparral shrub *Ceanothus megacarpus*. *Botanical Gazette* 147: 102–109.
- McMichael, C.E., Hope, A.S., Roberts, D.A. & Anaya, M.R. 2004. Post-fire recovery of leaf area index in California chaparral: a remote sensing-chronosequence approach. *International Journal of Remote Sensing* 25: 4743–4760.
- Moritz, M.A., Keeley, J.E., Johnson, E.A. & Schaffner, A.A. 2004. Testing a basic assumption of shrubland fire management: how important is fuel age? *Frontiers in Ecology and the Environment* 2: 67–72.
- Paysen, T.E. & Cohen, J.D. 1990. Chamise chaparral dead fuel fraction is not reliably predicted by age. *Western Journal of Applied Forestry* 5: 127–131.
- Regelbrugge, J.C. & Conard, S.G. 1996. Biomass and fuel characteristics of chaparral in southern California. 13th Conference on Fire and Forest Meteorology.
- Riggan, P.J., Goode, S., Jacks, P.M. & Lockwood, R.N. 1988. Interaction of fire and community development in chaparral of Southern California. *Ecological Monographs* 58: 156–176.
- Riggan, P.J., Franklin, S., Brass, J. & Brooks, F. 1994. Perspectives on fire management in Mediterranean ecosystems of southern California. In: Moreno, J.M. & Oechel, W.C. (eds.) *The role of fire in Mediterranean-type ecosystems*, pp. 140–162. Springer, New York, NY, US.
- Riggan, P.J., Wolden, L.G., Tissell, R.G., Weise, D.R. & Coen, J.L. 2010. Remote sensing fire and fuels in Southern California. In: Wade, D.D. & Robinson, M.L. (eds) *Proceedings of 3rd Fire Behavior and Fuels Conference*, October 25–29, 2010, Spokane, Washington, USA, pp. 1–14. International Association of Wildland Fire, Birmingham, AL, US.
- Rundel, P.W. & Parsons, D.J. 1979. Structural changes in chamise (*Adenostoma fasciculatum*) along a fire-induced age gradient. *Journal of Range Management* 32: 462–466.
- Schlesinger, W.H., Gray, J.T., Gill, D.S. & Mahall, B.E. 1982. *Ceanothus megacarpus* chaparral: a synthesis of ecosystem processes during development and annual growth. *Botanical Review* 48: 71–117.
- Schwilk, D.W. 2003. Flammability is a niche construction trait: canopy architecture affects fire intensity. *The American Naturalist* 162: 725–733.
- Specht, R. 1969. A comparison of the sclerophyllous vegetation characteristic of mediterranean type climates in France, California, and southern Australia. II. Dry matter, energy, and nutrient accumulation. *Australian Journal of Botany* 17: 293–308.
- Sprugel, D. 1983. Correcting for bias in log-transformed allometric equations. *Ecology* 64: 209–210.
- Weise, D.R., Zhou, X., Sun, L. & Mahalingam, S. 2005. Fire spread in chaparral — “go or no-go?”. *International Journal of Wildland Fire* 14: 99–106.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Map of aspect within each of the 60 m × 60 m study areas and 8 m × 8 m field plots, generated using a 10-m spatial resolution digital elevation model.

Appendix S2. Regression coefficients of stem above-ground biomass (AGB) in kilograms as a function of basal area (BA) in cm² for each species and stand age.

Appendix S3. Plot coordinates, area as measured by GPS coordinates, total plot biomass (excludes charred stem estimates) and total biomass per area for each plot age.