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Relationships between tree stand density and burn severity as measured by the Composite Burn Index following a ponderosa pine forest wildfire in the American Southwest

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ABSTRACT

The Trigo fire burned 5548 ha of the Manzano Mountains in central New Mexico in 2008. The fire burned with mixed severity through ponderosa pine (*Pinus ponderosa*) stands on the Cibola National Forest and private lands. The burned area exhibited a range of stand densities enabling this research to quantify the relationship between variation in tree density and burn severity using the Composite Burn Index (CBI) severity classification. Across 90 CBI plots, high tree density was strongly associated with high burn severity. The CBI method allowed classification of burn severity to a range of forest vertical fuels strata. Tree mortality and duff consumption are two attributes that recorded higher severity in plots with higher tree densities. The CBI approach is designed for rapid on-the-ground assessments; to compliment this procedure a rapid visual classification of stand density was tested to determine its accuracy for land managers. This visual assessment correlated well with quantitative measurements of tree density. Since density classes were also highly correlated with CBI scores they may therefore be a good predictor of burn severity in a stand. This is a more rapid way for land managers to categorize stand density than traditional density measurements. These findings demonstrate that reducing tree density in southwestern ponderosa pine stands may significantly lower burn severity resulting from wildfire.

1. Introduction

Ponderosa pine (*Pinus ponderosa*) forests in the American Southwest have experienced dramatic changes in physical structure, species composition, and ecological processes over the last century (Allen et al., 2002; Cooper, 1960; Covington et al., 1997; Fulé et al., 1997). Before Euro-American settlement, southwestern ponderosa pine forests were composed of low-density, park-like stands (Covington and Moore, 1994a) with dense grass understory and highly flammable leaf litter (Stone et al., 1999). Historically these forests experienced frequent low-severity surface wildfire (Kaufmann et al., 1998), creating heterogeneous forest spatial patterns at local and landscape scales (Allen et al., 2002). Disruption to the natural fire regime, harvesting, and intensive domestic livestock grazing practices of those forests have drastically altered their historic structure and has made them extremely vulnerable to unnaturally severe stand-replacing wildfires (Covington and Moore, 1994b; Swetnam et al., 1999), water stress, insect outbreaks (Kolb et al., 1998), and other deviations from historic conditions (Allen et al., 2002; Covington et al., 1997; Friederici, 2003; Moore et al., 2004).

In many watersheds throughout the Southwest, over 90% of ponderosa pine forests are considered at high risk of crown fires because of dense structure and unnaturally high levels of accumulated fuels (Allen et al., 2002; Covington and Moore, 1994a, 1994b). A major goal of ponderosa pine forest restoration is to renew natural stand structure and ecosystem function within a range of natural variability (Landres et al., 1999) and reverse unhealthy forest characteristics. Restoration usually includes some combination of reducing high-density stands through thinning, reintegrating natural disturbance through prescribed burning, and increasing species diversity and cover of native herbaceous understories (Brockway et al., 2002; Covington et al., 1997; Korb et al., 2003). Current understanding of fire behavior in the dry ponderosa pine forests of the Southwest is that crown fires occur as a transition from a surface fire to a crown fire, via ladder fuels (Graham et al., 2004), that then spread through the canopies, consuming tree crowns. Fuel management objectives therefore target the break down of fuel continuity both vertically and horizontally (Hunter et al.,

Abbreviations: CBI, Composite Burn Index; BAER, Burned Area Emergency Response.

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2007). The Southwest Forest Health and Wildfire Prevention Act (2004) (Public Law 108-317) was passed by the US Congress in 2004, outlining forest management measures to reduce the risk of wildfire to forests and municipalities in the Southwest. Forest thinning and prescribed fire treatments are recommended to improve overall forest health by enhancing wildlife habitat and biodiversity of forest communities; increasing tree growth and grass, forb, and shrub productivity; enhancing watershed values; and providing a basis for economically and environmentally sustainable forest uses.

A number of studies has evaluated the effectiveness of forest thinning on fire intensity and severity in southwestern ponderosa pine forests (Cram et al., 2006; Fulé et al., 2002, 2005; Pollet and Omi, 2002; Strom and Fulé, 2007), and all draw the common conclusion that untreated forests are at a higher risk of severe wildfire than treated areas. Agee and Skinner (2005) suggest that in order to make forests resilient to catastrophic wildfire, some form of forest thinning is required. The authors propose that forest treatments to reduce fire severity comprise four basic principles: (1) reduce surface fuels using mechanical methods or prescribed fire; (2) increase the height to the live crown; (3) decrease the crown density, reducing the chance of crown fire spread; and (4) keep mature trees of fire-resistant species (e.g., ponderosa pine) that would reduce overall mortality in the event of surface fire and move the forest back to historical stand structures.

Pollet and Omi (2002) suggest that the removal of small-diameter trees may be beneficial for reducing crown fire hazard in ponderosa pine sites. Prescribed fire may be effective at reducing these small-diameter trees, but only after some form of mechanical thinning has occurred to prevent these mid-canopy trees transmitting fire to the overstory canopy. In Pollet and Omi's (2002) study of four fires throughout western North America, treated stands with lower densities and larger trees have experienced lower burn severities than untreated stands. The authors attribute those findings to less continuous crowns and ladder fuels in stands with fewer trees (i.e., ladder fuels provide vertical continuity between the surface fuels and crown fuels, increasing the likelihood of torching and crowning [Pollet and Omi, 2002]). Cram and Baker (2003) have found similar results in that treatment areas up to 20 years old experience lower burn severity, ground char, and fireline intensity during wildfire. The researchers find that crown damage and fireline intensity are positively related to basal area and density. Similarly, Strom and Fulé (2007) have found that average tree density is substantially greater in untreated areas, and following a wildfire about half the trees survive in treated areas compared to only 5% in untreated areas.

The measure of burn severity in empirical studies has been complicated by its numerous definitions in the literature (Chappell and Agee, 1996; Lutes et al., 2003; Lyon and Stickney, 1976; Wang, 2002; Wells et al., 1979; Neary et al., 2005; Cocke et al., 2005), and as a result no universal measure of burn severity exists (Key and Benson 2006). Instead metrics are adopted for studies based on ecological and management objectives and scale (Cocke et al., 2005). One of the most applicable of definitions comes from Ryan and Noste (1983), who suggest that severity classification should be a combination of soil and overstory effects, stating that burn severities are fire effects that incorporate both upward (fireline intensity) and downward (heat per unit area) heat pulses. This incorporates parameters that are readily measurable. It is well accepted that burn severity essentially integrates the physical, chemical, and biological changes occurring in an area as a consequence of fire (White et al., 1996). Fire can have immediate effects on the aerial sections of trees, with canopy height dictating the impact from the flames. Applying the Ryan and Noste (1983) definition, burn severity to trees is related to the intensity of the fire (flame length). However, it is important to note that the most severe fires might not always be the ones in which a forest canopy is completely consumed. Damage to the underlying duff and forest floor may be more destructive to future tree regeneration. This emphasizes the relevance of measuring severity in more than one stratum.

In 1999, Key and Benson (1999) introduced the Composite Burn Index (CBI). Although this index was developed to provide a standardized method of burn severity classification and to overcome the ambiguity inherent in the literature, Key and Benson (2006) acknowledge that CBI does not represent the 'true' severity. Key and Benson (2006) describe burn severity as the magnitude of change to components existing at the time of the fire. Instead of focusing on individual strata as have past methods (Chappell and Agee, 1996; Whittle et al., 1997), the CBI adopts a multi-strata approach to severity, because according to Key and Benson (2006), vertical levels in a forest have different biophysical components and multiple levels impart structural complexities that profoundly influence fire behavior. Key and Benson (1999) suggest that ratings that incorporate all strata seem to improve the overall measure of severity because they incorporate damage to both the ground, surface and canopy layers (Key and Benson, 1999). CBI is described as being suitable for use in a variety of forest and woodland types, and thus is readily transferable between sites and the standard measuring tools ensure repeatability (Cocke et al., 2005; Lutes et al., 2003). A major focus of CBI is that it is considered to be a more cost-effective, efficient approach to burn severity monitoring, relying on visual assessment of conditions. CBI is designed specifically to be used in monitoring large-scale burns (Key and Benson, 1999), typically in conjunction with an imaging differencing methodology – Normalized Burn Ratio (NBR)(Key and Benson (2006)) which assesses differences in bands 4 and 7 from pre-fire and post-fire remote sensed images. CBI was developed as a means of ground truthing these images on large scale burns. The Trigo fire burned 5548 ha of the Manzano Mountains in central New Mexico in April and May 2008. The fire burned in ponderosa pine and mixed conifer forests, with mixed severity, and most of the area burned during singular wind-dominated runs (most notably a run on April 30, 2008). At the time of the fire researchers were involved in an un-related long-term study on the impact of hazardous fuels reduction on watershed health and water yield. Research plots from that longterm study were burned by the Trigo fire, providing the opportunity to investigate the impact of fire on watershed processes. Since that original research focused on the effect stand density had on watershed processes, similarly this wildfire provided us with the opportunity to quantify the relationship between ponderosa pine density and burn severity. Previous studies that have measured the effect of thinning treatments on burn severity have noted that treatment and control plots can often exhibit similar stand characteristics in terms of density and basal area (Pollet and Omi, 2002; Skinner et al., 2004; Strom and Fulé, 2007). The Trigo fire burned across private and public US Forest Service lands with various treatment histories and previous thinning prescriptions, resulting in a landscape of variable tree densities, including treated areas and untreated stands with similar tree densities. This variable treatment history hindered the direct comparison of stands based on pre-fire treatment status alone. Instead this study evaluates the burn severities recorded among a range of tree densities in stands that may be treated or untreated. The hypothesis of this study was that denser stands (those with more trees per hectare) experienced greater degrees of burn severity when compared to less dense stands.

In addition to studying the impact that tree density has on burn severity, this study also tested the utility of a rapid methodology for tree density classification to expedite assessments of density by land managers. A qualitative ocular methodology was compared to standard density measures to determine its accuracy and utility.

Furthermore, the CBI measures were also compared to the BAER severity map that was created for the fire. Since no one severity index is considered a standard (Key and Benson, 2006), this study provides verification of the severity scores measured on the ground, and also serves to ground truth the BAER map that is routinely used to direct post-fire restoration activities. This study was carried out in August 2008, three months following the Trigo fire.

2. Materials and methods

2.1. Study area

The Trigo fire was one of three fires (also Ojo Peak and Big Springs) that burned in late 2007 and 2008 on the eastern slopes of the Manzano Mountains, New Mexico (Fig. 1). The fire is thought to have started by human ignition on April 15, 2008, and burned 5548 ha of the Manzano Mountains, including lands in the Cibola National Forest and Grassland, and private lands close to the communities of Manzano, Torreon, and Tajique, New Mexico. The burned area ranged in elevation from 2076 to 2827 m and comprised piñon-juniper woodland to ponderosa pine and mixed conifer forest. The climate within the project area is temperate and characterized by relatively light annual precipitation, a wide range of diurnal and annual temperatures, abundant sunshine, and low relative humidity, factors that combine to create semiarid climatic conditions. Elevations above 2743 m are typically cooler and moister with a sub-humid climatic regime. The mean annual temperature in the project area is 11.9 °C and mean annual precipitation is 394.00 mm, with the majority of precipitation occurring in July and August during monsoonal moisture patterns that produce high intensity storms, lightning activity, and multiple fire ignitions. The mean annual snowfall is 54.4 cm. During April 2008, the average temperature recorded at a weather station within the fire perimeter on private lands was 9.04 °C with the total precipitation yielding 0.4 cm. This is compared to an April average temperature of 9.7 °C and precipitation of 1.7 cm taken from a long-term weather station in Estancia, New Mexico, over a 90-year period (Western Regional Climate Center, 2012). The topography in the area ranged from steep and rocky on the western edge of the fire to gently rolling plains on its eastern perimeter. This study area was situated in the northeastern portion of the burn in stands consisting almost entirely of ponderosa pine and with minimal slope; all measurement plots had an eastern aspect.

The study area was located in Lower Montane Coniferous Forest, Ponderosa Pine/Gambel Oak Series (Dick-Peddie, 1993), within the Arizona/New Mexico Mountains Ecoregion (Griffith et al., 2006). Higher elevation areas to the west of the study area, also burned by the Trigo fire, were dominated by Upper Montane Coniferous Forest, White Fir/Douglas-fir/Ponderosa Pine Series (Dick-Peddie, 1993). According to common stand exams completed in the area by the Cibola National Forest in 2012, tree densities (trees greater than 13 cm diameter at breast height) ranged from 84 to 3188 trees ha^{-1}. Most stands displayed 7–1604 trees measuring less than 13 cm diameter at breast height per hectare. Overall, canopy closure was greater than 60%. Stands were primarily even-aged, lacking structural diversity (SWCA Environmental Consultants, 2012). The eastern fringe of the fire terminated in an area of piñon-juniper woodlands with total tree densities ranging from 62 to 2194 trees ha^{-1} and greater than 60% canopy closure. All the CBI plots were located in the ponderosa pine forest types. Understory vegetation was limited but included Gambel oak (*Quercus gambelii*), blue grama (*Bouteloua gracilis*), and mountain muhly (*Muhlenbergia montana*).

The Trigo fire burned with mixed severity as shown by the Burned Area Emergency Response (BAER) map of the incident (Fig. 2). BAER classifies high severity as foliage consumed, moderate severity as foliage completely scorched, low severity as patchy foliage scorch, and unburned as foliage unscorched. There were very few unburned areas within the fire perimeter on which to sample. The highest severity burn occurred in the upper montane coniferous forest and ponderosa pine forest to the west of the study area, which coincided with steeper terrain at the highest elevations.

2.2. Sampling design

Ninety sampling plots were randomly located on private and US Forest Service lands within a 174 ha area of the northeastern portion of the burn, all within former and remaining ponderosa pine forest (see Fig. 2). In order to isolate the effect of tree density (essentially fuel) on fire behavior and hence burn severity, the other two components of the fire behavior triangle – weather (temperature, wind and relative humidity) and topography, were controlled (Pyne et al., 1996; Graham et al., 2004) by selecting plots that burned during a single burn period (April 30th, 2008) and were on comparable slope and aspect (<10% slope and east facing aspect). These random plots were located using a random point generator within the defined sampling area which comprised 174 ha of the total burn area.

Plots were also stratified equally among four different BAER severity classifications (unburned, low, moderate, and high). The intent was to compare the BAER classification of severity with a measured CBI severity classification at each plot (Table 1). The mosaic of BAER severity types on the landscape provided spatial intermixing of plots representing the different severity types. After navigating to each plot, we ensured that each plot was situated within a relatively homogenous area, 60×60 m of the same fire effects. Plots were spaced at least 90 m following CBI protocols. Each plot was circular with a radius of 15 m. Stand density varied across the plots providing the opportunity to compare tree density and burn severity. The plots were visited once in August 2008, three months after the fire. In CBI terms this was considered an "initial assessment" (Key and Benson, 2006), and the most appropriate time to measure immediate post-fire severity before the fire effects that represent severity are obscured or lost (Pollet and Omi, 2002).

2.3. Composite Burn Index measurements

The CBI methodology was used to classify severity because it allowed quick, accurate, and consistently repeatable measurements of the magnitude of severity across a large burn area. CBI is designed to assess burn severity within the first growing season after a fire. The CBI score represents an average of observable fire effects throughout a plot. The fire effects attributes, or "rating factors," are rated by criteria that correspond to identified burn levels along a gradient from unburned to extremely burned conditions (Fig. 3). Each attribute is individually scored as decimal increments ranging in increments of 0.1, from 0.0 to 3.0.

Rating factors were taken from Key and Benson (1999) and are grouped into five vertical strata throughout each plot representing: (A) ground surface substrates, (B) herbs and shrubs less than 1 m tall, (C) tall shrubs and trees 1–5 m tall, (D) intermediate-sized trees (sub-canopy), and (E) big trees (upper canopy, co-dominant/dominant) (see Fig. 3).

CBI plots were circular-nested plots consisting of a 10-m-radius plot inside a 15-m-radius plot. The smaller plot was used to measure the first three strata (A, B, and C), which were averaged per plot to provide an aggregate score of burn severity to the understory. The larger outer plot was used to measure fire effects to the intermediate and big trees (D and E), which similarly were

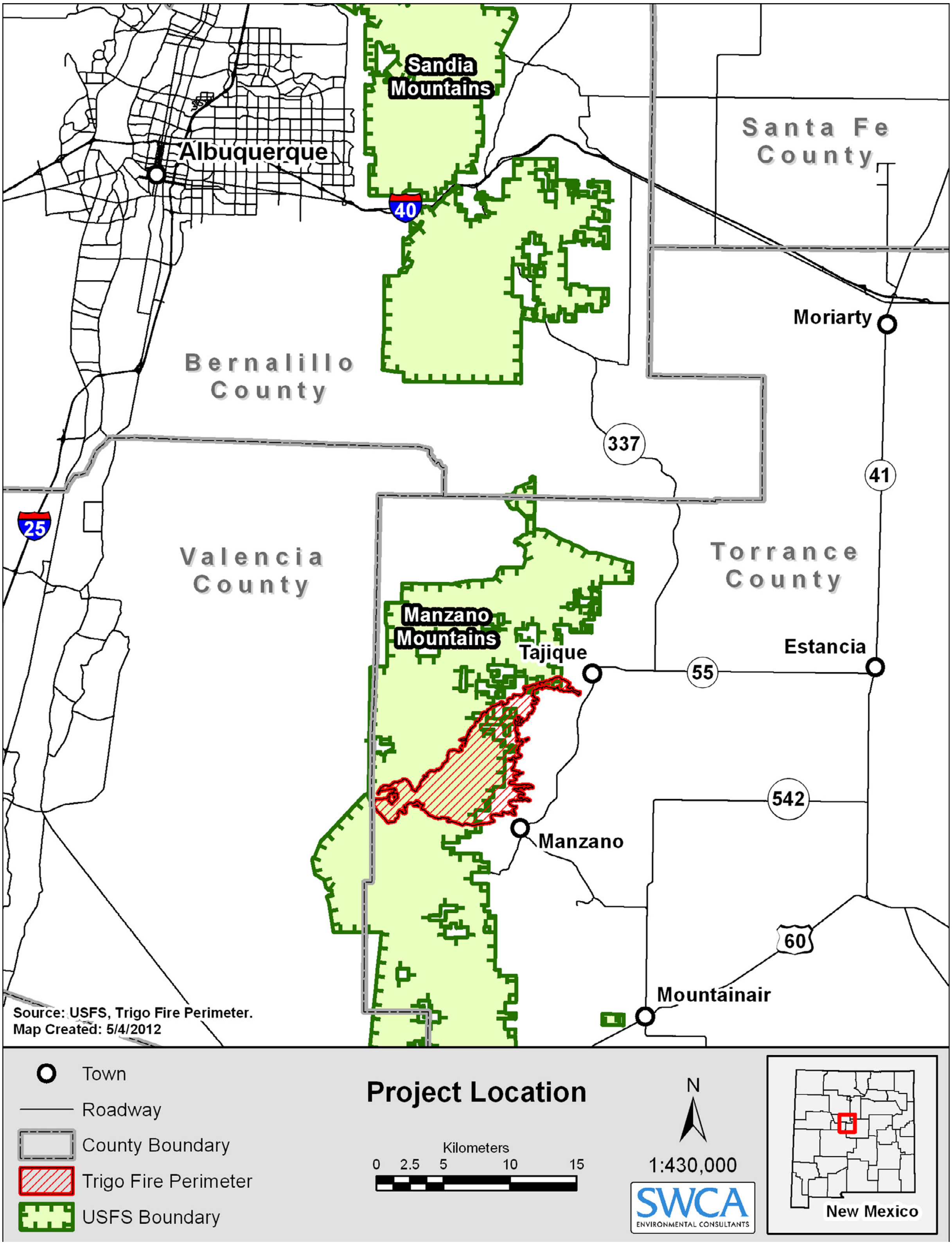

Fig. 1. Trigo fire, Manzano Mountains of central New Mexico.

combined to generate an average overstory severity score per plot. CBI values were calculated for the understory and overstory strata, and then a total plot CBI was calculated by averaging those two values. Fig. 4 shows photograph examples of four CBI plots along with associated CBI scores and adjective ratings. All measurements were visual estimates of fire damage to parameters across the plot, and measurements were reached by consensus among researchers at each plot. Data were recorded on a standard CBI field data form (see Fig. 3), assigning CBI scores to each of the 23 rating factors (if present) (Key and Benson, 2006).

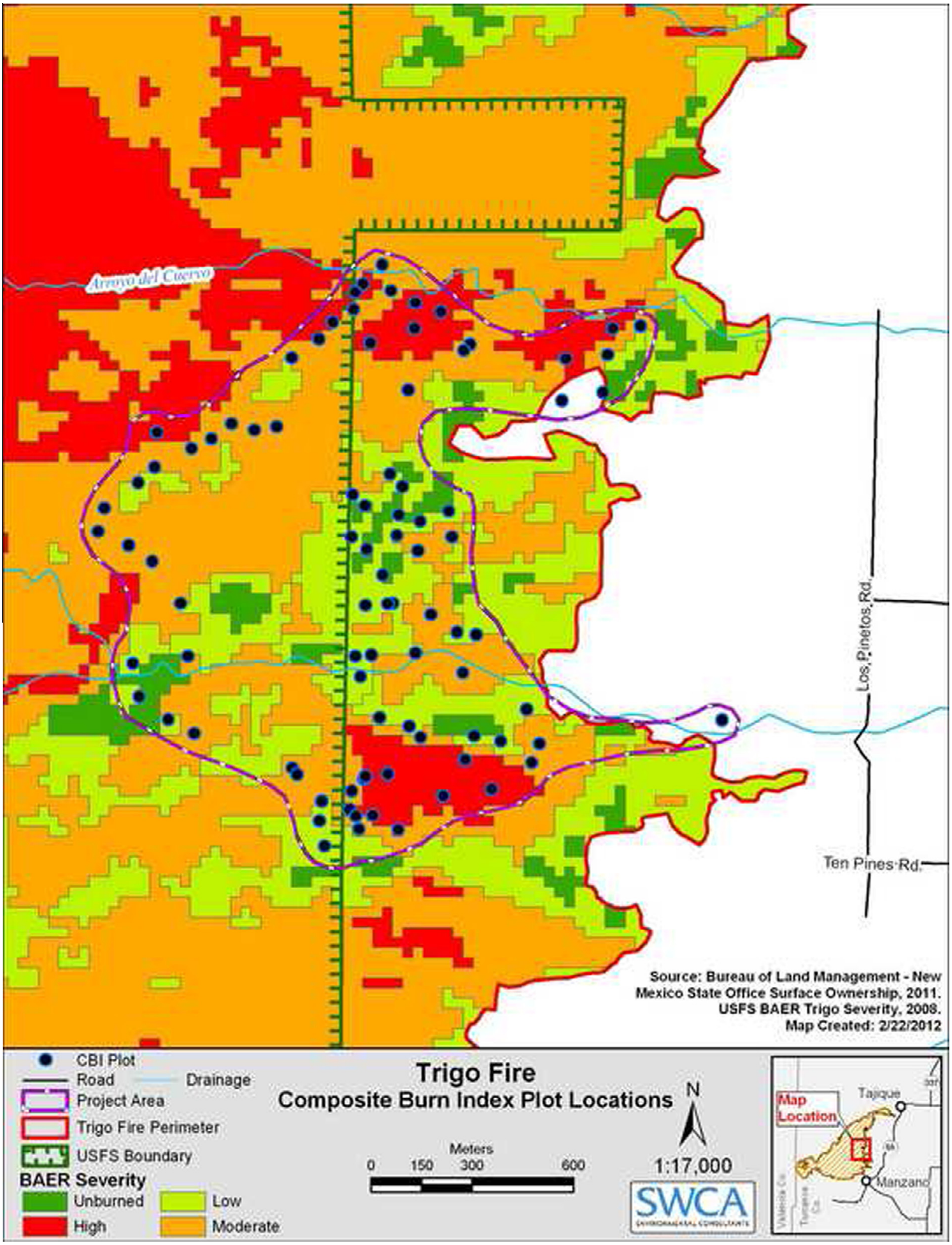

Fig. 2. Location of study plots within the Trigo fire burn perimeter, central Manzano Mountains, New Mexico.

2.4. Tree density classification

Tree densities on each plot were recorded as trees per hectare and basal area. Trees per hectare were determined using the fixed area plot method (Avery and Burkhart, 2002) with a radius of 8 m, while basal area was determined by point sampling (Avery and Burkhart, 2002) with a basal area factor of 15. Both these methods were conducted from the same center point at each measurement plot. Tree densities were also recorded by density classes, generated from visual assessment of each plot from plot photographs.

Table 1
Relationship between CBI scores and adjective ratings and BAER severity.

CBI score	CBI adjective severity rating	BAER severity
0.0–0.5	No effect	Unburned
0.5–1.5	Low	Low
1.5–2.5	Moderate	Moderate
2.5–3.0	High	High

Both methods were used in order to test the accuracy of visual assessment of density. The CBI methodology is designed for rapid assessment of burn severity, so visual assessment of stand density may prove useful for land managers carrying out a large-scale assessment of burn areas if it is found to be comparable to quantitative measures of density.

Plots were rated by density into five density classes from 1 (low density) through 5 (high density). Fig. 5 shows examples of each of the five density classes among our study plots. Classification was based upon visual assessment of trees/plot from plot photographs taken at the time of the CBI measurements. The actual density measurements and visual assessments of density were completed by two independent research crews to avoid measurement bias.

2.5. Data analysis

The relationship between visual estimates of tree densities (five rank levels) and measured tree densities over the 90 study plots was compared using non-parametric Spearman-rank correlation analysis to test for a significant, positive relationship. This test was intended to determine whether visual densities were accurate. The relationship between total CBI scores per plot and BAER burn severity levels also were examined by use of Spearman-rank correlation analysis to determine whether there was a significant positive relationship between the two types of burn severity indices. Spearman-rank correlation analysis also was used to examine relationships among all specific CBI variables.

Data across all 90 plots were used to produce averages and ranks for all CBI variables to examine the relationships among CBI scores, tree density classes, actual tree densities, and BAER severity scores. Specifically, we examined whether CBI scores were predicted by tree density classes with ordered logistic regression analysis for total CBI scores and for each subscore variable component of the total CBI scores across the five vertical strata:

- Understory, Stratum A – Substrates: litter/light fuel consumed, duff, medium fuels, heavy fuels, and soil and rock cover/color.
- Understory, Stratum B – Herbs, Low Shrubs and Low Trees < 1 m: percent foliage altered and frequency percent living.
- Understory, Stratum C – Tall Shrubs and Low Trees, 1–5 m: percent foliage altered, frequency percent living, and percent change in cover.
- Overstory, Stratum D – Intermediate Trees: percent green (unaltered), percent black (torched), percent brown (scorched/girdled), percent canopy mortality, and char height.
- Overstory, Stratum E – Big Trees (Upper Canopy): percent green (unaltered), percent black (torched), percent brown (scorch/girdled), percent canopy mortality, and char height.

Analyses were performed for each CBI variable within each vertical strata layer and based on values of all variables averaged over all strata and canopy layers (total CBI). Ordered logistic regression was used because tree density classes and CBI scores are categorical data with ordered rankings. For all statistical testing, a standard alpha level of $p < 0.05$ was used to test for the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis (of no difference) was true.

3. Results

The correlation analysis revealed a significant positive relationship between visual tree density estimates and actual measurements of tree density across all of the study plots ($r = 0.70$, $p < 0.0001$) (Fig 6). Correlation analysis demonstrated a significant positive relationship between total plot CBI scores and BAER burn severity scores ($r = 0.63$, $p < 0.0001$), both providing similar measures of burn severity (Fig. 7). It also indicated that all of the individual CBI variables were highly positively correlated among each other.

Ordered logistic regression analysis demonstrated that tree density classes were significant predictors of total CBI scores (averaged overall variables and vertical strata) ($p < 0.0001$) (Fig. 8). Regression analysis of each CBI parameter subscore from each of the five vertical strata also revealed that all of those CBI scores also were significantly predicted by tree density classes except for combined data across the two variables of the herbaceous plant layer, Stratum B (Table 2).

Mean or average values of all CBI-scored variables within vertical strata across the five tree density classes are presented in Fig. 9 for understory strata (A–C) and in Fig. 10 for overstory strata (D and E). Those mean values show trends for increasing CBI scores with increasing tree density classes. Within the understory Stratum A, CBI scores for litter, duff, medium fuels, heavy fuels, and change to soil and rock cover/color all followed the same trends for increasing scores with increasing tree density classes. However, those trends were not uniform increases, instead indicating a slight relative decrease in CBI scores for tree density class 4, but increasing again to the highest CBI scores for density class 5. CBI scores for percent foliage altered and frequency percent living within understory Stratum B also revealed similar trends with a slight decrease for tree density class 4. However, the variable percent foliage altered increased only slightly across tree density classes. Variables representing the shrub and sapling tree layer, understory Stratum C, all demonstrated the same increasing trend in CBI scores relative to tree density, again with a slight decrease for density class 4. This anomaly relating CBI scores to density class 4 may have resulted from ocular error in discerning subtle density differences between high tree density classes 3, 4 and 5, a researcher may be better able to accurately distinguish large differences between the low and high density classes than among high density classes.

Variables within the tree overstory Strata D (intermediate canopy) and E (upper canopy) also demonstrated similar increasing trends in CBI scores relative to tree density. However, differences in Stratum D were greater among tree density classes for percent black torched and percent canopy mortality than for the other variables of percent green, percent brown scorched, and char height (Fig. 10). Variables within Stratum E also revealed similar increasing trends in CBI scores across tree density classes. However, char height differences across density classes was not as pronounced as differences in percent green, percent black torched, percent brown scorched, and percent canopy mortality. Examination of CBI scores averaged over all variables per understory and overstory strata separately, and total CBI scores averaged over all variables for both understory and overstory, also showed strong trends for increasing CBI scores with increasing tree density classes (Fig. 11).

Logistic regression analysis confirmed that tree density was a strong predictor of CBI score, or burn severity. Table 2 provides the results of logistic regression tests for the relationships between

FIREMON LA Form

BURN SEVERITY -- COMPOSITE BURN INDEX (BI)

PD - Abridged	Examiners:			Fire Name:	
Registration Code		Project Code		Plot Number	
Field Date mmddyyyy	/ /	Fire Date mmyyyy	/		
Plot Aspect		Plot % Slope		UTM Zone	
Plot Diameter Overstory		UTM E plot center		GPS Datum	
Plot Diameter Understory		UTM N plot center		GPS Error (m)	
Number of Plot Photos		Plot Photo IDs			

BI – Long Form	% Burned 100 feet (30 m) diameter from center of plot =						Fuel Photo Series =	
STRATA RATING FACTORS	BURN SEVERITY SCALE							FACTOR SCORES
	No Effect	Low		Moderate		High		
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	
A. SUBSTRATES								
% Pre-Fire Cover: Litter = Duff = Soil/Rock =	Pre-Fire Depth (inches): Litter = Duff = Fuel Bed =							∑ =
Litter/Light Fuel Consumed	Unchanged	--	50% litter	--	100% litter	>80% light fuel	98% Light Fuel	
Duff	Unchanged	--	Light char	--	50% loss deep char	--	Consumed	N =
Medium Fuel, 3-8 in.	Unchanged	--	20% consumed	--	40% consumed	--	>60% loss, deep ch	
Heavy Fuel, > 8 in.	Unchanged	--	10% loss	--	25% loss, deep char	--	>40% loss, deep ch	$\bar{X}$ =
Soil & Rock Cover/Color	Unchanged	--	10% change	--	40% change	--	>80% change	
B. HERBS, LOW SHRUBS AND TREES LESS THAN 3 FEET (1 METER):								
Pre-Fire Cover =	% Enhanced Growth =							∑ =
% Foliage Altered (blk-brn)	Unchanged	--	30%	--	80%	95%	100% + branch loss	
Frequency % Living	100%	--	90%	--	50%	< 20%	None	N =
Colonizers	Unchanged	--	Low	--	Moderate	High-Low	Low to None	
Spp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High change	$\bar{X}$ =
C. TALL SHRUBS AND TREES 3 to 16 FEET (1 TO 5 METERS):								
Pre-Fire Cover =	% Enhanced Growth =							∑ =
% Foliage Altered (blk-brn)	0%	--	20%	--	60-90%	> 95%	Signifcnt branch loss	
Frequency % Living	100%	--	90%	--	30%	< 15%	< 1%	N =
% Change in Cover	Unchanged	--	15%	--	70%	90%	100%	
Spp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High Change	$\bar{X}$ =
D. INTERMEDIATE TREES (SUBCANOPY, POLE-SIZED TREES)								
Pre-Fire % Cover =	Pre-Fire Number Living =			Pre-Fire Number Dead =				∑ =
% Green (Unaltered)	100%	--	80%	--	40%	< 10%	None	
% Black (Torch)	None	--	5-20%	--	60%	> 85%	100% + branch loss	N =
% Brown (Scorch/Girdle)	None	--	5-20%	--	40-80%	< 40 or > 80%	None due to torch	
% Canopy Mortality	None	--	15%	--	60%	80%	%100	$\bar{X}$ =
Char Height	None	--	1.5 m	--	2.8 m	--	> 5 m	
Post Fire: %Girdled =	%Felled =			%Tree Mortality =				
E. BIG TREES (UPPER CANOPY, DOMINANT, CODOMNANT TREES)								
Pre-Fire % Cover =	Pre-Fire Number Living =			Pre-Fire Number Dead =				∑ =
% Green (Unaltered)	100%	--	95%	--	50%	< 10%	None	
% Black (Torch)	None	--	5-10%	--	50%	> 80%	100% + branch loss	N =
% Brown (Scorch/Girdle)	None	--	5-10%	--	30-70%	< 30 or > 70%	None due to torch	
% Canopy Mortality	None	--	10%	--	50%	70%	%100	$\bar{X}$ =
Char Height	None	--	1.8 m	--	4 m	--	> 7 m	
Post Fire: %Girdled =	%Felled =			%Tree Mortality =				

Community Notes/Comments:	CBI = Sum of Scores / N Rated:	Sum of Scores	N Rated	CBI
	Understory (A+B+C)			
	Overstory (D+E)			
	Total Plot (A+B+C+D+E)			

% Estimators: **20 m Plot:** 314 m² 1% = 1x3 m 5% = 3x5 m 10% = 5x6 m
30 m Plot: 707 m² 1% = 1x7 m (<2x4 m) 5% = 5x7 m 10% = 7x10 m

After, Key and Benson 1999, USGS NRMSC, Glacier Field Station.
Version 4.0 8 27, 2004

Strata and Factors are defined in FIREMON Landscape Assessment, Chapter2, and on accompanying BI "cheatsheet." www.fire.org/firemon/lc.htm

Fig. 3. Standard CBI field data sheet showing the variables scored within vertical strata layers (Key and Benson, 2006).

CBI scores and tree density classes, partitioned by CBI scores for each variable within strata, each stratum overall, understory and overstory overall, and total CBI. Note that ordered logistic regression does not provide regression coefficients like linear regression, so amounts of variation predicted by tree density classes for each response variable are not available to report. In general, all variables and grouped variable categories resulted in highly significant regression models indicating that tree density was a strong predictor of CBI score/burn severity. However, regression results for the pooled Stratum B were not significant, even though regression

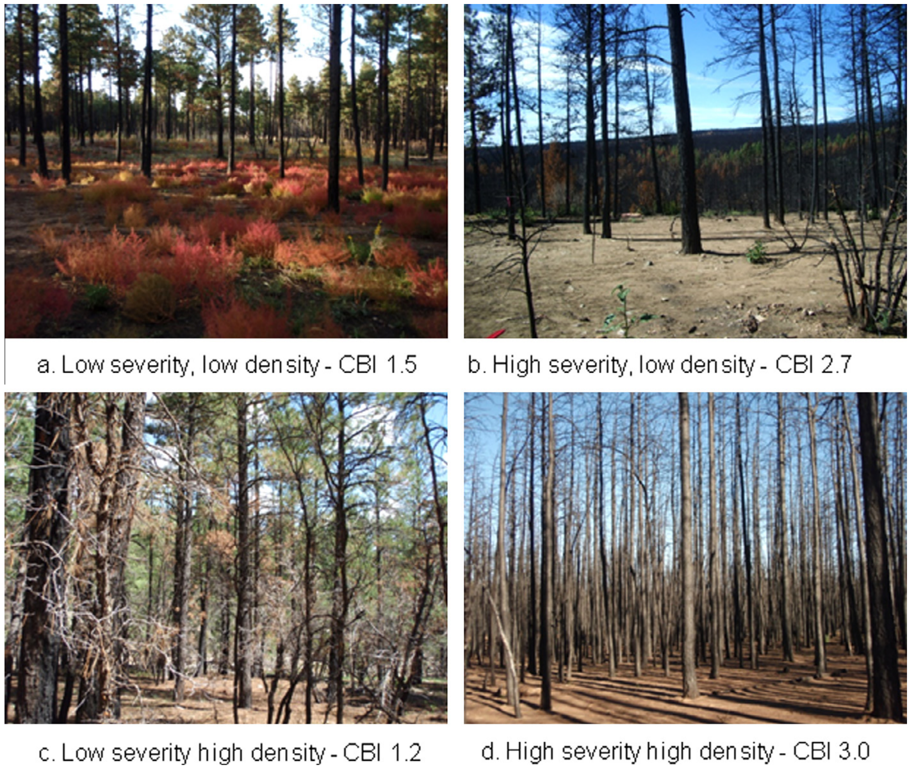

Fig. 4. Examples of four of the tree density classes and associated CBI scores from four of the Trigo fire study plots.

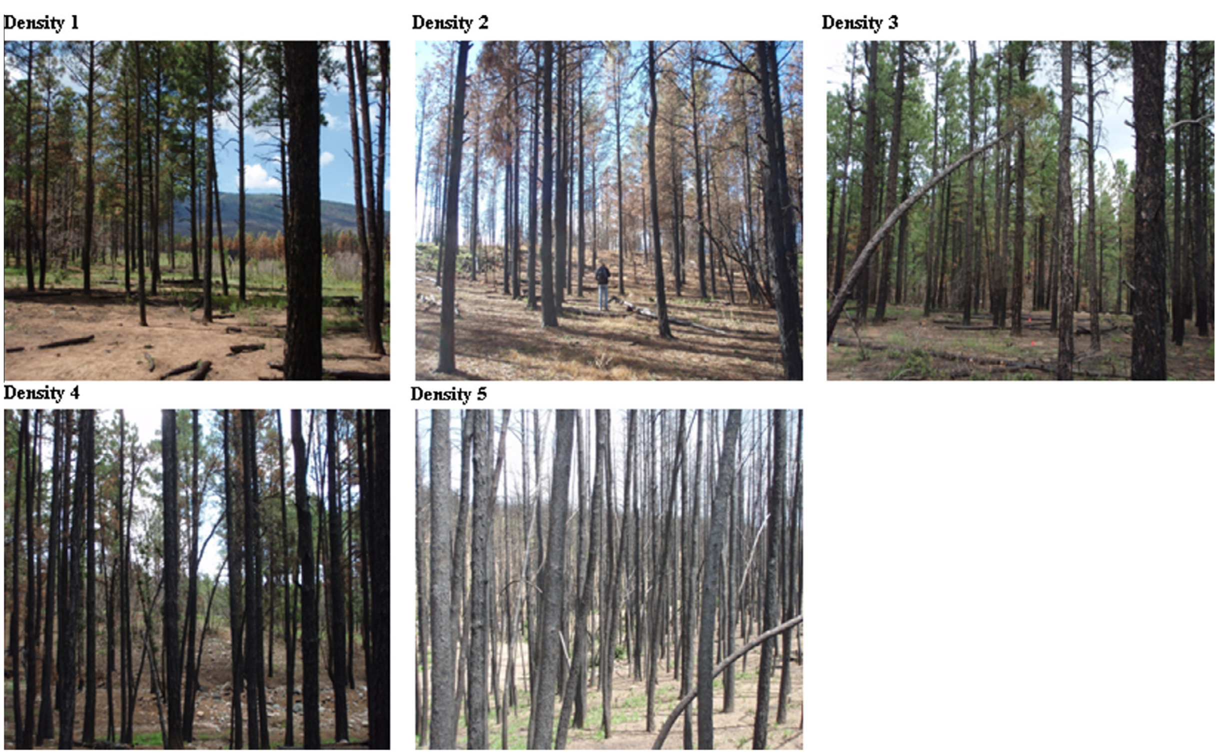

Fig. 5. Examples of all five tree density classes from study plots in the Trigo fire.

models for each Stratum B variable were, indicating some contrasting relationships among those individual variables relative to tree density. The Stratum B layer in this system was poorly represented because the high stand density prevented establishment of a significant herbaceous layer and regeneration was minimal throughout the sample area. This could explain the poor contrasting relationship that was observed. However, stratum B contributes to fire spread, intensity and behavior, therefore land managers should carefully consider the composition of this layer when making management decisions.

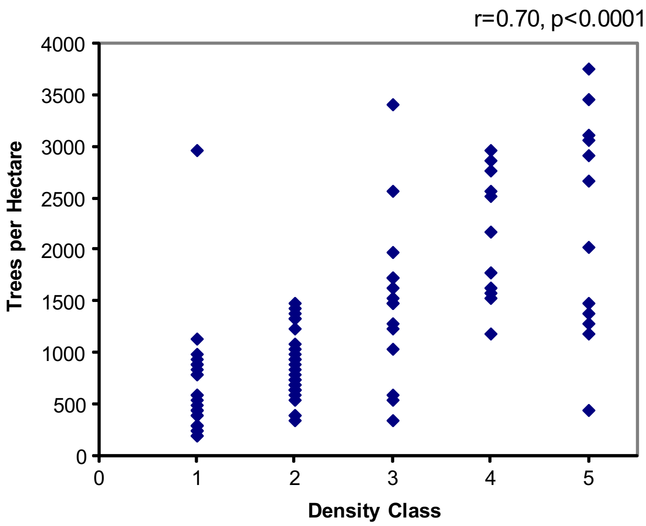

Fig. 6. Relationship between measured tree density and ocular density classes.

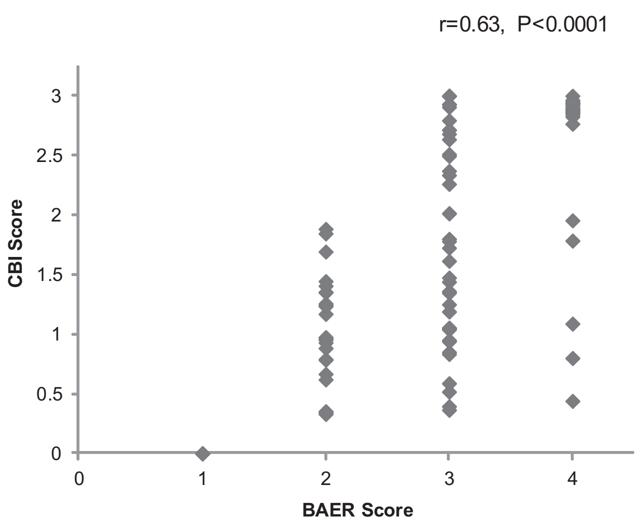

Fig. 7. Relationship between BAER and total CBI burn severity scores.

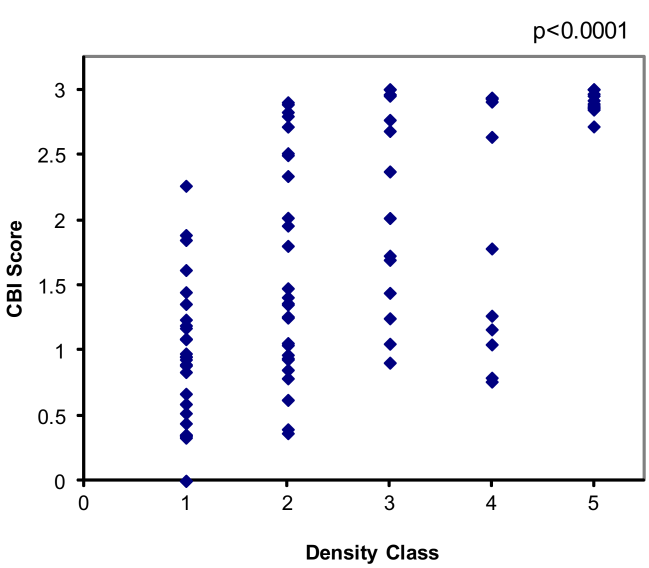

Fig. 8. Relationship between ocular tree density classes and total CBI scores.

Table 2
Ordered logistic regression results for relationships between CBI scores and tree density classes. CBI scores were partitioned into total, understory and overstory, all strata, and all variables within strata.

Dependent variable	*p* Value
CBI total	<0.0001
CBI understory	<0.0001
CBI Stratum A	<0.0001
Litter	<0.0001
Duff	<0.0001
Medium fuel	<0.0001
Heavy fuel	<0.0001
Soil and rock cover/color	<0.0001
CBI Stratum B	0.4380
Herbaceous change	0.0287
Herbaceous% living	<0.0001
CBI Stratum C	<0.0001
Shrub foliage altered	0.0079
Shrub% living	<0.0001
% Change in cover tall shrubs/sapling trees	<0.0001
CBI overstory	<0.0001
CBI Stratum D	<0.0001
% Green unaltered intermediate canopy	<0.0001
% Black torched intermediate canopy	<0.0001
% Brown scorch intermediate canopy	<0.0001
% Canopy mortality intermediate canopy	<0.0001
Char height intermediate canopy	<0.0001
CBI Stratum E	<0.0001
% Green unaltered upper canopy	<0.0001
% Black torched upper canopy	<0.0001
% Brown scorch upper canopy	<0.0001
% Canopy mortality upper canopy	<0.0001
Char height upper canopy	<0.0001

4. Discussion

The Trigo fire burned with mixed severity across 5548 ha, and because it burned across private and US Forest Service lands, pre-fire timber management intensity varied considerably, making it difficult to execute a study of burn severity based on treatment status alone. Varying stand densities in the burn area, however, allowed burn severity measurements on a plot level to be compared to tree density. Measurements were taken less than three months after the fire, allowing initial burn severity assessments to be made before fire effects were obscured by salvage operations and natural processes.

Plots that exhibited lower tree densities experienced significantly lower overall burn severity than high tree density plots. The null hypothesis (H_o) that stand density had no influence on burn severity in ponderosa pine forests is rejected in favor of supporting the research hypothesis (H_a) that burn severity effects were higher in denser stands of ponderosa pine. This is in accordance with previous studies showing stands that have been treated to reduce tree density having exhibited lower burn severity following wildfire (Cram and Baker, 2003; Cram et al., 2006; Pollet and Omi, 2002; Martinson and Omi, 2003; Strom and Fulé, 2007). These studies have also shown that stands with fewer trees have less continuous canopies and ladder fuels (Pollet and Omi, 2002), which reduce the potential for crown fire initiation. In our study, severity measurements of overstory trees, including crown scorch and crown consumption, were significantly greater for plots in the higher density classes (and higher number of trees per hectare). Similarly, severity measurements of understory attributes such as duff consumption and changes to soil color and composition were significantly greater for higher tree density plots.

As has been noted by other authors (Graham et al., 2004; Pollet and Omi, 2002), there are many factors that may govern fire behav-

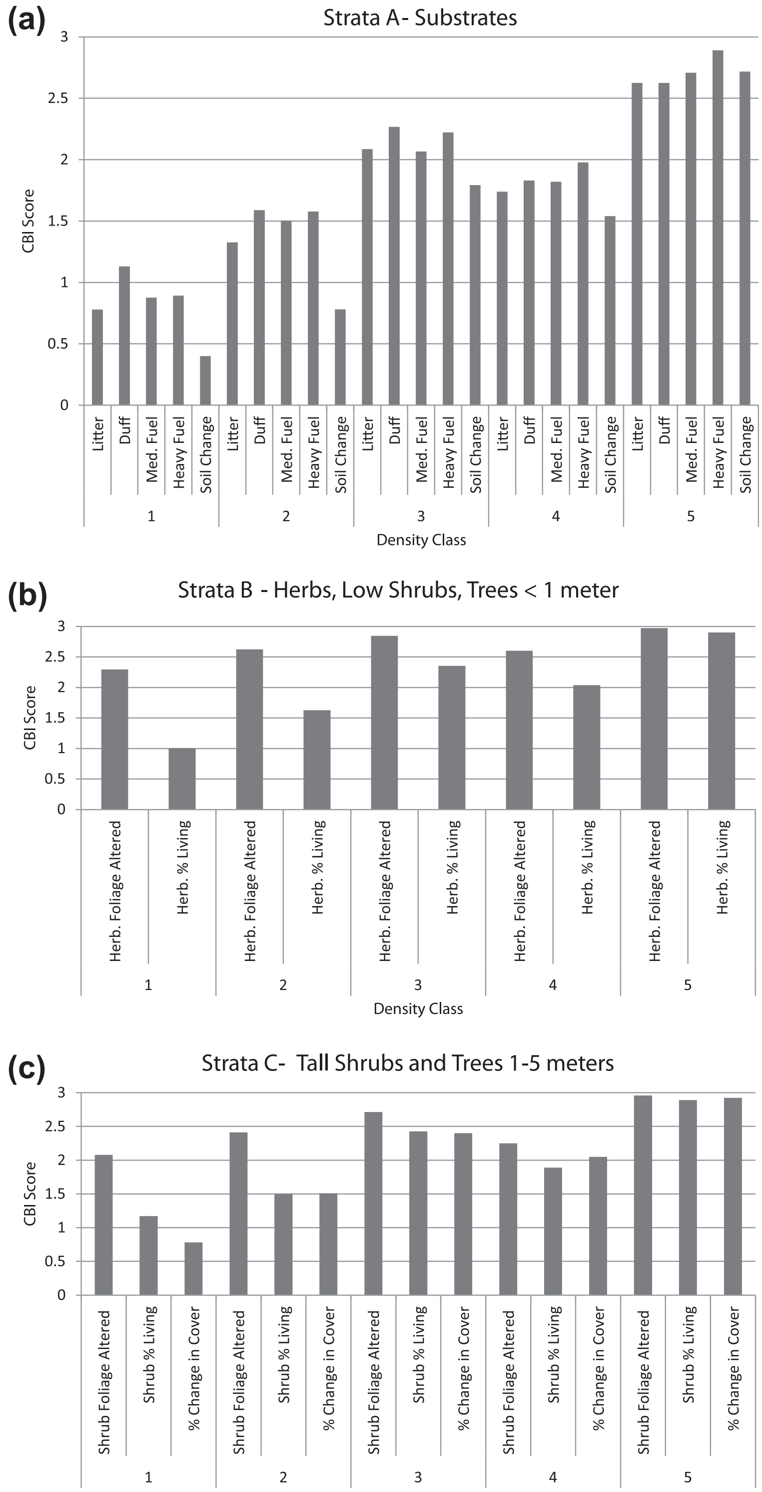

Fig. 9. (a–c) Density class against CBI score for understory Strata A–C.

ior and severity. A combination of factors occurring at multiple spatial scales influences the way a fire burns (Bradshaw et al., 2003). This study attempted to reduce influences of other variables on burn severity by only measuring plots in stands that burned during a single burn period (hectares burned during a fire run on April 30, 2008), in which weather is assumed to have been as constant as is empirically possible, and by locating plots on similar slope and aspect, and away from other topographic influences that would affect fire behavior (Chandler et al., 1991). By isolating all other variables to the greatest extent possible, variations in forest structure (discussed here in terms of density) appear to have contributed to the observed diversity in burn severity.

Strom and Fulé (2007) found that burn severity was more closely coupled with the arrangement of tree fuels, distributed among many smaller trees versus fewer larger ones, than the total amount of tree fuels. Pollet and Omi (2002) found this to be the case, also

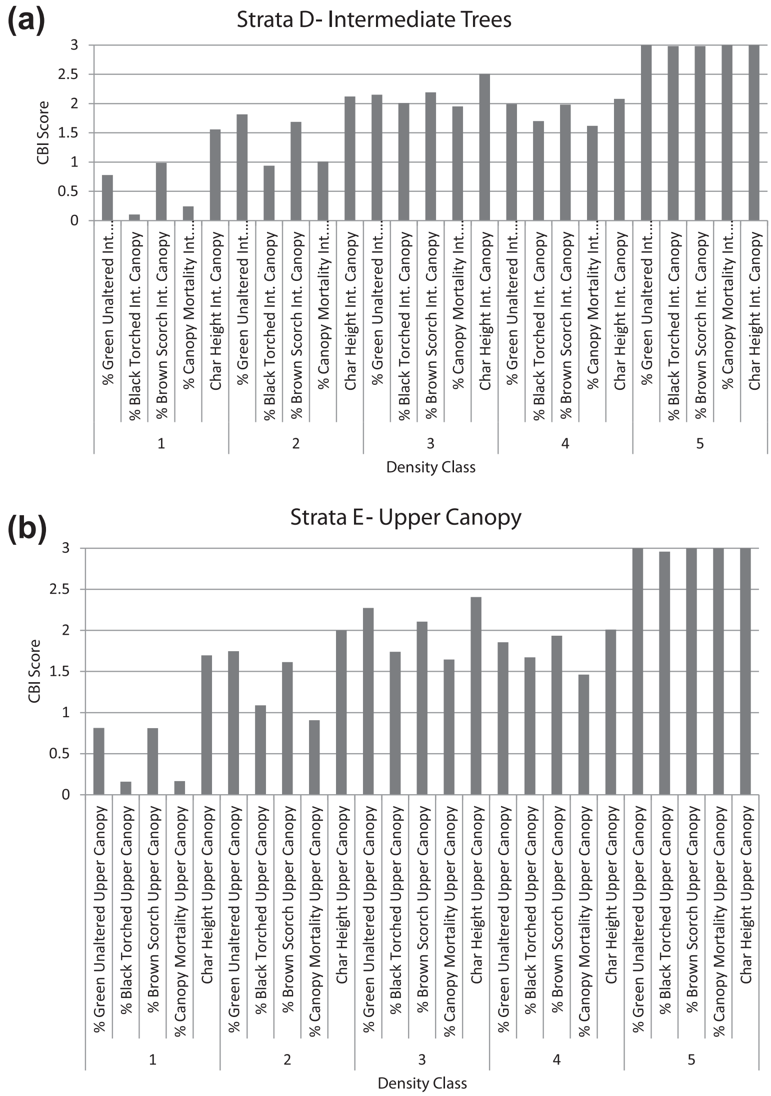

Fig. 10. (a and b) Density class against CBI Score for overstory Strata D and E.

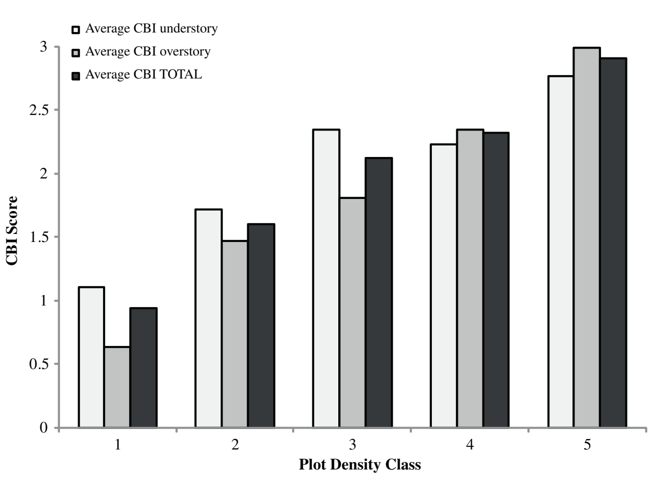

Fig. 11. Average CBI ratings (1 = low severity, 3 = high severity) for 90 plots distributed on private and public land throughout the Trigo burn area. Plots are classified by tree density (1 = low density to 5 = high density) and bars represent understory burn severity, overstory burn severity, and overall plot burn severity.

noting that average tree diameter on a plot was closely related to burn severity. Average tree diameter was not recorded in this study, but anecdotal evidence suggests that lower density stands were composed of fewer larger trees as compared to a large number of smaller trees in the higher density stands. Analysis revealed that basal area had no influence on burn severity in this study, perhaps because plots with a large number of small-diameter trees (therefore in a higher density class) had similar basal areas when compared to plots with a few large-diameter trees (therefore in a low density class). Pollet and Omi (2002) also found that tree density differences between treated and untreated plots were often greater than basal area differences.

Graham et al. (2004) suggested that fire behavior and severity are dependent on the properties of the fuel strata and the continuity of the fuels both horizontally and vertically. Trees contribute to the canopy or aerial fuels in a stand (Graham et al., 2004). Crown fire is closely related to the continuity of the canopy, crown bulk density, and canopy base height (Albini, 1976; Rothermel, 1991). Stands with greater tree density in the form of small-diameter trees and saplings have more ladder fuels and continuous crowns that increase the spread of active crown fire (Agee and Skinner, 2005) and therefore, generate more severe fire effects (MacCleery et al., 1995; Pollet and Omi, 2002; Weaver, 1943). The severe fire effects observed in the high density stands (e.g., 100% canopy consumption and 100% tree mortality) suggest these stands burned by active crown fire through continuous canopies. Because of the canopy consumption in those stands, one can only infer from the fire effects the original canopy closure and bulk density. Forest thinning treatments often target a reduction of crown bulk density as a means of mitigating crown fire hazard (Agee, 1996; Graham et al., 1999, 2004). From this inferences can be made that lower density stands in this study exhibited a lower crown bulk density.

Another factor found to heavily influence fire behavior and crown fire initiation are dead and downed surface fuels and fuel moisture (Agee et al., 2002; Albini and Reinhardt, 1995; Pollet and Omi, 2002). Surface fuels are an important component of the fuel complex, and often crown fires are initiated by propagation from a surface fire into the canopy via ladder fuels (Van Wagner, 1977). Because this study was *post-facto*, it was not possible to quantify the pre-fire surface fuel loadings to determine the impact that surface fuels had on the overall burn severity on a plot. Unlike other studies (Cram et al., 2006; Pollet and Omi, 2002) that have assessed the impact of fuel treatment on burn severity, it is not possible to make assumptions regarding surface fuels based on treatment type.

CBI was designed to be an efficient methodology suitable for evaluating large-scale burns (Key and Benson, 1999). The CBI method was quick and effective and the large numbers of variables, though daunting in appearance, were easy to assess and required limited equipment. CBI provided a comprehensive assessment of multiple strata, allowing a more refined measure of severity throughout the entire vegetative community. Each individual variable showed significant trends of increasing burn severity with increasing density. These variables were also found to be highly correlated with each other, suggesting that land managers could reduce the number of variables measured and still obtain an accurate determination of burn severity across multiple strata. The only exception to this was for Stratum B where the percent foliage altered and the frequency percent living variables, though significant predictors of density when taken separately, were insignificant when pooled to a strata level. These variables appear to have contributed to contrasting relationships with tree density. This may have been due to the CBI scoring for percent foliage altered, where even in low-severity burn areas 100% of the foliage of herbaceous plants and sapling trees were often altered, giving a high CBI score (see Fig. 3). Moreover, the herbaceous layer for Stratum B was poorly represented due to the dense overstory impeding grass and forb establishment and canopy cover. In a system were this layer is more prevalent, one may expect differing results from this strata. Furthermore, in areas of low severity, where the understory layer was dominated by resprouting species, such as Gambel oak, as was the case in this study, the presence of resprouting individuals meant that plots received a low CBI score for frequency percent living. This meant a plot could score 3.0 for percent foliage altered, but 1.0 for frequency percent living.

Another explanation for the Stratum B results is the accuracy with which percent foliage altered scores were assigned. In many cases there were insufficient adjacent reference sites with which to determine pre-fire presence of forbs and low shrubs, so CBI scores for this variable may not have been accurately assigned. In cases where reference sites are limited or where the strata is poorly defined or represented, Key and Benson (1999) suggest excluding that variable from the index, which may have been appropriate in this study.

A strong positive relationship was observed between CBI scores for Stratum A and tree density class. Since there tends to be strong relationships between stand development phase and the composition of the substrates, this relationship between CBI scores and Stratum A may actually be at least in part a function of the development phase and not entirely a result of density class.

Unlike other indices that attribute severity based on assessment of the canopy or surface substrate alone (Chappell and Agee, 1996; Whittle et al., 1997), CBI is sensitive to burn severity in some of the mid-canopy strata, the very strata that are integral in the transmission of fire from the surface to the crowns. By observing damage to this mid-canopy, which includes tall shrubs and sapling trees, land managers can determine if damage to the canopy is a result of ladder fuels or if the fire moved by active crown fire, independent of surface fire and ladder fuels. This also may enhance the classification of moderate burn severity, which has in the past been obscured by the oversimplified differentiation of fire effects into ground or overstory effects (Ryan and Noste, 1983).

CBI is becoming a popular field-based classification that is used for ground verification of remotely sensed imagery of burn severity (Cocke et al., 2005). This study examined the utility of CBI by comparing severity scores with severity classifications developed by the BAER team assigned to the fire. The CBI scores were highly correlated with the BAER team severity classifications. In this way CBI serves as a ground-truthing tool for remotely sensed images or could also serve as an efficient method for land managers to monitor burn severity where remote sensing is not available. Monitoring of burn severity, especially as it relates to forest structure is imperative if land managers are to learn how fire behavior varies with fuels across a landscape. Lessons learned from accurate classification of burn severity can assist managers in developing effective fuels reduction treatments in the future.

In order to compliment this rapid burn severity monitoring tool, the utility and accuracy of a visual assessment of stand density was tested. Density classes (1–5) were found to correlate highly with measurements of trees density. This is significant since many land managers have limited time available to carry out detailed measurements of stand structure. Using a photo series, similar to that used for fuel model classification (Ottmar et al., 2007), land managers could classify stand densities from a photograph of each stand and use this to aid in fuel planning on a forest-wide scale. This technique is especially promising since the density classes have been found to correlate highly with the degree of burn severity exhibited from wildfire in ponderosa pine. This method has now been tested on one fire, in one location, and in one forest type, additional research is needed to test its applicability in other forests. However, for land managers in relatively dry ponderosa pine forest types, these findings indicate that CBI is a useful post-fire severity assessment and management tool.

A possible limitation of the study was that although forest structure was evaluated in terms of tree density and basal area, the relationships between surface fuels or canopy density and burn severity were not evaluated. The visual classification of density, however, did discriminate plots based on the relative crown closure. One can only make an assertion that once a certain tree density threshold is reached, then crown bulk density is sufficient to generate crown fire spread. Variability in stand structure across landscapes and regions, require that photo indices be calibrated across numerous forests to build a standard photo set that would be fully transferable across a broader region. However, forest managers could develop their own photo index for use in their particular management areas, making the concept transferable between regions. Adjustments to the method might include reducing the number of density classes from 5 to 4 and producing a coarser scale, where differences in density are more easily discernible by land managers. Such an approach could alleviate the anomaly observed in this study between CBI scores and density class 4.

Another challenge to this study is the well established concept that no one severity classification necessarily represents the true severity (Key and Benson, 2006). This problem can be alleviated by employing a number of indices simultaneously in each study, as was attempted here by using the BAER classification scheme in comparison to the CBI method. Additional research could also employ the NBR image differencing method or utilize additional ground methodology (Ryan and Noste, 1983, Turner et al. 1994, Moreno and Oechel, 1989).

5. Conclusions

Since this study was based on one fire and one forest type it cannot be used to predict effects on other fires in the region or other forest types, but findings from this study demonstrate interesting relationships between tree density and burn severity in ponderosa pine, similar to findings from numerous other authors (Cocke et al., 2005; Cram et al., 2006; Pollet and Omi, 2002). The CBI scores were positively and significantly related to tree density estimates. The burn severity scores across the spectrum of densities examined in this study indicate that reducing the tree density of a stand should in turn reduce the severity of fire effects during a wildfire. Fuel reduction treatments that recommend reducing the density of ponderosa pine stands mainly through the removal of small-diameter trees are also well supported in the literature (Cram et al., 2006; Fiedler et al., 2002; Pollet and Omi, 2002; Strom and Fulé, 2007). Most recent empirical studies suggest a combination of treatment methods is the most effective way of mitigating catastrophic wildfire in southwestern ponderosa pine. Mechanical tree removal followed by periodic prescribed burning to reduce surface fuels has been advocated by many (Agee and Skinner, 2005; Graham et al., 1999, 2004; Peterson et al., 2003). Fuel reduction treatments should be employed to manage forests for much lower tree densities leaving larger and widely spaced residual trees (Pollet and Omi, 2002). Such treatments will likely reduce the chances of developing large crown fires (Graham et al., 2004) that impact human and ecological resources and values such as were seen during the Trigo fire.

This evaluation of post-wildfire relationships between tree density and burn severity using the CBI burn severity classification demonstrated that CBI scores and standard BAER fire severity scores were very similar, and that CBI provided an accurate and efficient method for characterizing post-fire burn severity. Using the visual density class approach may provide a more rapid way for land managers to categorize stand density than traditional density measurements. Based on the findings from this study, CBI and tree density class estimates are recommended as cost-effective methods for evaluating post-fire severity.

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