FINAL REPORT

Age-class Mosaics and Wind-driven Fire: Further Fuel for the Debate

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Principal Investigator: Jan L. Beyers, Plant Ecologist

Co-Principal Investigators: Philip J. Riggan, Ecologist
David Weise, Research Forester
Timothy Paysen, Research Forester (retired)
Marcia Narog, Ecologist

Affiliation (all): U.S. Forest Service, Pacific Southwest Research Station
4955 Canyon Crest Drive
Riverside, CA 92507

I. Abstract

In 2006 the Santa Ana wind-driven Esperanza fire burned through the North Mountain Experimental Area (NMEA) and vicinity, including the scars of 10 previous fires. Multiple images of the fire's progression were taken using PSW Research Station's airborne FireMapper thermal-imaging system. Existing fuels data and historic NMEA maps plus new fire images were used to investigate relationships between vegetation history, fire behavior and severity, and fuel consumption. Soil samples were collected at a subset of fire severity sample points to assess seed bank survival. Coordinated documentation of vegetation recovery addressed the effects of age class and fire severity on chaparral regeneration and non-native species invasion.

Ground sampling of fuel characteristics combined with remote sensing demonstrated that the multispectral FireMapper instrument can provide an improved means to acquire the needed pre and post-fire fuels data necessary for quantitative, high-resolution measurement of wildland fire. Detailed analysis of the field data and remotely sensed data showed that the standard fire behavior fuel models for chaparral and grass did not capture the range of fuel loading associated with elevation and stand age. Fuel loading showed a general correspondence with observed fire behavior (radiant heat release ($W\ m^{-2}$). Southwestern spread of the Esperanza Fire was contained near boundaries of previous fires and young fuels. Fuel, fire perimeter, and energy release data from FireMapper roughly agreed with simulation results from the CAWFE model.

We were able to use FireMapper imagery to identify and differentiate various landscape features on vegetation plots to transect resolution. This included separation of general plant characteristics such as large compared to small leafed species. Sequential images reflected the increased plant cover observed from repeated measurements of vegetation plots. This technology appears to have utility for monitoring general plant cover recovery for large and/or remote areas.

Areas containing older chaparral stands (>50 years since last fire at the time of the Esperanza fire) and higher fuel loading corresponded to areas of higher burn severity (as determined by ground crews). Species richness was greatest in mid-age burns (11-50 years since previous fire). At three years post-fire, non-native grasses were the most abundant cover type. Non-native species dominated both burned and unburned fuel breaks.

II. Background and Purpose (one to two pages)

Management plans for the four southern California national forests identify virtually every acre of National Forest System land as part of the wildland-urban interface (WUI) environment, because any fire start could burn into human development within one burning period. Vast areas of these national forests are covered in chaparral, an evergreen shrubland of thick-leaved plants that typically burns in stand-replacing fires. Almost as volatile as the fuel itself has been an ongoing debate about the natural fire regime and patch-size dynamics in chaparral stands. Minnich (2001) argued that the fine-grained mosaic of chaparral patch sizes observed in Baja California, Mexico, where effective fire suppression has not been practiced, provides a model for what southern California chaparral once was and should be: there, fires burn older chaparral but tend to go out on their own when they meet young stands under most burning conditions. Keeley and associates (Keeley and Fotheringham 2001a, 2001b; Moritz et al. 2004) contended that autumn Santa Ana winds (strong off-shore foehn winds) have always produced very large fires in southern California, and given the ever-increasing number of anthropogenic fire starts, effective suppression of small fires is the only thing that keeps urban-proximal chaparral from burning too frequently on a large scale.

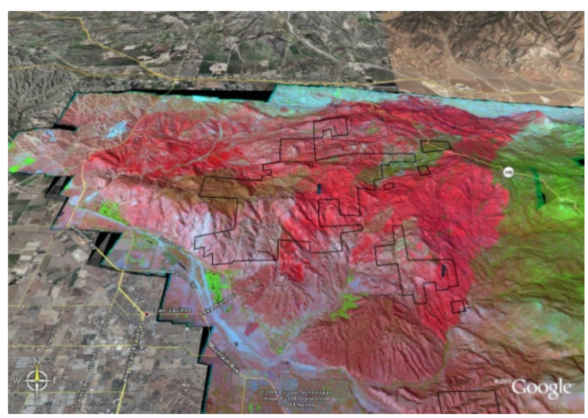
This continuing debate about the role of chaparral age class mosaics in modifying fire size and behavior under wind-driven conditions complicates managers' ability to implement prescribed burns in remote areas to reduce fuels for WUI protection. Opponents of back-country burn projects fear that inevitable large fires will reburn young fuels, leading to chaparral regeneration failure and type-conversion to weedy grassland (Keeley 2006). While long intervals between fire may lead to the loss of species that are dependent upon fire ("senescence risk"), short fire return intervals may lead to the loss of species that cannot reach reproductive maturity between fire events ("immaturity risk") (Zedler 1995). At present, immaturity risk from short fire return intervals is considered to be the greater threat in southern California chaparral, due to frequency of anthropogenic ignitions (Zedler 1995, Stephenson and Calcarone 1999). Public concern and opposition can put prescribed burn projects on indefinite hold.

The Santa Ana wind-driven Esperanza fire of 2006 burned through the North Mountain Experimental Area (NMEA) and adjoining lands, including areas burned in 15 previous fires, which occurred from 1918 to 2005, as well as some areas with no recorded fire history. Initial observations revealed that substantial areas within the mapped fire perimeter were skipped by the fire or lightly burned (Fig. 1), despite strong Santa Ana winds on the day the fire started. Multiple images of the fire's progression were taken using the Forest Service Pacific Southwest Research Station's (PSW) airborne FireMapper thermal-imaging system (Fig. 2). Existing fuels data and historic NMEA maps plus the new fire images provided an opportunity to investigate relationships between vegetation history and fire behavior and severity to address the patch mosaic debate.

The proximity of seed sources for invasive non-native plants can affect whether or not a burned area is heavily invaded. Several large historic fuel breaks run through the NMEA (Blandford 1962, Plumb et al. 1963); vegetation on them was dominated by grasses and opportunistic sage scrub species such as California buckwheat (*Eriogonum fasciculatum*) before the Esperanza fire. The fuel breaks offered an opportunity to look for evidence of herbaceous species spread out into burned chaparral, testing the conclusions drawn in Merriam et al. (2006).

Figure 1. Burn mosaic pattern, Esperanza fire, NMEA.

Figure 2. FireMapper image of burned area.



Project Objectives

The project had two main objectives: 1) determine fire severity and estimate fire behavior for a Santa Ana wind-driven fire that burned through a variety of chaparral age classes, ranging from quite old to only several years, and evaluate vegetation recovery, particularly in the younger stands most susceptible to "immaturity risk" from anthropogenic fire; and 2) ground-truth during- and post-fire imagery from PSW's FireMapper system in order to expand the utility of this instrument for public land managers. Specific project objectives were:

1. Use fire history maps, historic aerial photos, and shrub remnants to reconstruct the fuel age mosaic within the Esperanza fire and compare that to postfire severity mosaic and remaining vegetation condition mosaic.
2. Ground-truth airborne thermal imagery to ground-based estimates of fire intensity, using plant remnants (base and skeleton) and existing data about vegetation/fuel structure to reconstruct likely fuel structure. Develop correlations between observed thermal intensity and progression with apparent intensity and fire effects, increasing the utility of the FireMapper instrument for characterizing fire behavior.
3. Determine the relationship between fire severity, postfire imagery, and chaparral seed bank survival in a variety of vegetation age classes and fire severities.
4. Use airborne imagery to monitor postfire vegetation recovery and correlate it with ground measurements to develop methods for using the FireMapper platform for landscape-scale vegetation evaluation.
5. Evaluate the consequences of "immaturity risk" where wind-driven fire encountered younger fuels by documenting vegetation recovery for three seasons after the Esperanza fire.
6. Document distribution of invasive non-native species in relation to fuel breaks and roads within the fire area and relate abundance to vegetation age class and fire history.

III. Study Description and Location

Study Site

Our study site was the Esperanza fire (39,855 acres near Banning in Riverside County, CA); we focused on areas covered by aerial thermal imaging. Samples areas were generally on the San Bernardino National Forest (SBNF) and Bureau of Land Management (BLM) lands, including the North Mountain Experimental Area (NMEA). Most of the study was conducted on NMEA (33°50' N, 117°54' W). The 10,740 acre NMEA is covered predominantly in chamise (*Adenostoma fasciculatum*) chaparral between 730 and 1,280 m (2,400 and 4,200 ft) elevation on soils derived from granitic rock and mica-schists. Most of NMEA is a mosaic of various fires that occurred during the last 50 years, with some areas fire-free since records have been kept. Nearly 61% of NMEA is within the mapped perimeter of the Esperanza fire.

Methods

Work Conducted Prior To Receiving JFSP Funding

Remote Sensing: High-resolution images were collected during the Esperanza Fire aboard a twin-engine Piper Navajo (N70Z) with a FireMapper®[1] thermal-imaging radiometer (Riggan and Hoffman 2003), a Sensors Unlimited digital camera operated at a short-wave-infrared wavelength of 1.6 μm (equivalent to Landsat Thematic Mapper band 5), and Kodak MegaPlus 1.6i digital cameras. The FireMapper is an airborne thermal imager that utilizes a single uncooled microbolometer array and a series of filters to measure radiant emissions in the 8.5 – 12.5 μm wavelength and in two narrow bands centered at 9 and 12 μm (Riggan et al. 2003). Changes in reflectance at 1.6 μm wavelength appear to be useful in mapping gradients in chaparral canopy coverage (P.J. Riggan, *unpublished data*) and in discriminating fire effects associated with different age classes of chaparral and intensity of burning (Riggan et al. 1994). Four cameras in standard configuration provide wavelength bands comparable to Landsat Thematic Mapper bands 3, 4, 5, and 6. FireMapper images with an uncooled micro-bolometer detector array. Through-the-lens calibration and drift correction provided consistent and reliable measurements. The 1.8-

[1] Trade names are provided for information purposes only and do not constitute endorsement by the U.S. Department of Agriculture.

milliradian optics of the FireMapper and Sensors Unlimited cameras provide a nominal resolution of 1.8 m at 1000 m altitude. The 1.6i cameras have a nominal resolution of 0.36 m at this altitude.

FireMapper thermal imagery was collected during the Esperanza Fire a total of eight times over the three day period of active burning. The aircraft elevation was such that each image pixel covered an area approximately 5 m by 5 m. Post-processing of the raw image files involved classifying the measured radiance into 19 classes which corresponded to estimated ground surface temperatures of 50 to > 750°C (Fig. 1). Classes 1-4 (50 to 100°C) were excluded from this analysis because of the possibility that they did not burn. Thus 15 classes representing temperatures from 100 to > 750°C were grouped into three categories: low = 5-9, moderate = 10-14, and high = 15-19. The total estimated areas of these categories are found in Table 1.

Table 1. Estimated area classified into fire temperature categories from FireMapper imagery (Weise and Riggan 2007).

Category	Temperature (°C)	Area (ha)
Low	101 - 300	876.0
Moderate	301 - 550	90.6
High	551 - >750	1.9

Fire intensity and fuel consumption: Fuel consumption and fire intensity class were assessed using circular plots 16.2 m^2 (radius = 2.26 m) in size. Sample locations were determined randomly within each fire intensity category. The sampling objective was to sample 90 plots of known intensity equally distributed within each fire intensity category. An additional 60 plots were located in areas where no active or residual burning was observed by FireMapper. At each plot, an onsite assessment of the intensity class was made using the following criteria: high intensity = virtually all above ground biomass consumed; moderate intensity = fine fuels and small branches consumed; low intensity = majority of fine fuel still on plants.

For all shrubs that originated within the plot, the basal diameter of each stem 10 cm above the ground was measured. An attempt to identify the plant species as chamise, ceanothus (*Ceanothus* spp.), scrub oak (*Quercus berberidifolia*) or manzanita (*Arctostaphylos* spp.) was made. Each plant was visually divided vertically into two height classes (≤1 m and >1 m). Countryman and Philpot (1970) reported that chamise branches greater than 1.28 cm diameter are typically not consumed by wildfire. For each height class, a go-nogo gauge was used to classify the burned tip branch diameter into 4 classes: 0 - 0.32, 0.33 - 0.64, 0.65 - 1.27, and 1.28 - 2.54 cm. Up to six tip diameters were measured for each height strata around the plant.

Sample points were marked and GPS coordinates recorded. Using unpublished biomass equations developed from data collected at North Mountain Experimental Area, we 1) estimated the fuel loading before the fire from the basal diameter and 2) used the tip diameters to estimate the amount of fuel consumed. Fuel consumption was used to produce a map of fire intensity, which was compared spatially with the measured thermal intensities.

<u>Work Conducted With JFSP Funding</u>

Soil seed bank description: Soil cores were collected from two depths (0-2 cm and 2-5 cm) at a subset of the locations used for fuels and fire severity characterization (65 of 145 possible sample points) during summer the first year post-fire (lack of field personnel precluded collecting samples sooner).

Very little rain fell during the winter of 2006-2007, and little vegetation regrowth was noted. Five cores were collected from around each point and combined by depth. Soil cores were air-dried and then stored in a cold room until planting. The samples were spread on top of soilless medium in flats in a greenhouse at the PSW-Riverside lab and allowed to germinate. Germinated seedlings were counted, identified to species whenever possible, and removed. Some seedlings that couldn't be identified were removed from the experimental flats and planted out in pots until they flowered. Photographs and voucher specimens helped with subsequent identification. Seeds in the soil samples were given almost a year to germinate.

Post-fire vegetation recovery under different thermal intensities and stand ages: Post-fire vegetation recovery was assessed at sites representing different burn severities and pre-fire vegetation age classes (generally the same subsample of fuel consumption points as used for soil seed bank collection with addition of a few points in younger stand ages). Sampling was conducted during mid to late summer the second year postfire and in late spring to early summer the third year.

Ground measurements of vegetation regrowth were made using the line-point method described in FIREMON (Fire Effects Monitoring and Inventory System; see link at http://www.frames.gov). Macroplots were established each point, with five 20-m line-point transects run parallel on general slope contours from a baseline located 5 m from the fuel sampling location. At 40 points along each transect a pointer was dropped, and each species of plant touched was recorded, along with a ground cover category, for a total of 200 sample points per plot. Number of hits for each species was totaled and divided by 2 to give percent cover. In addition, shrub resprouts and seedlings were counted by species in a 1-m wide belt along each transect. Height and two crown diameters were measured on up to three shrubs of each species in each belt to give an estimate of recovering fuel volume.

To map vegetation recovery, we used a combination of NDVI, thermal IR, and short-wave IR Landsat Thematic Mapper (TM5) imaging at the end of the summer in each year of the study. Post-fire aerial imaging specifically estimated the Normalized Difference Vegetative Index (NDVI) – a ratio used to estimate leaf area and detect drought stress. To accomplish this, FireMapper measurements of long-wave or thermal-infrared radiances in three wavelength ranges (8.1 to 9.0 μm, 11.4 to 12.4 μm, and 8.1 to 12.4 μm) and our Kodak 1.6i camera's images at 550 nm (green light), 650 nm (red light) and 850 nm (near-infrared light) were collected. The three channels were used on an exploratory basis to develop an estimator for ground measurements in the different plots. We used 1-meter resolution in red and near IR data (NDVI) and 5-meter resolution for thermal and short-wave IR.

Fuel breaks as source of non-native species: Spread of non-native species from major fuel breaks within the burned area was assessed using the method described in Merriam et al. (2006). Ten sample points were spaced at 322 m (0.2 mi) intervals along three fuel breaks located along major (dirt) roads at NMEA. Quadrats 1-m^2 in size were placed along transects running from the center of the fuel break out into the area of burned chaparral at each point. Transects were sampled at 5 and 10 m into the fuel break and at 5, 10, 20 and 40 m into the adjacent chaparral. Cover by plant species was determined by ocular estimate in each quadrat. Two students from Redlands University investigated whether native species colonized further into the fuel breaks by determining plant cover in 5 quadrats in the fuel break near each of the points we had marked. They presented their results as their senior capstone paper.

IV. Key Findings

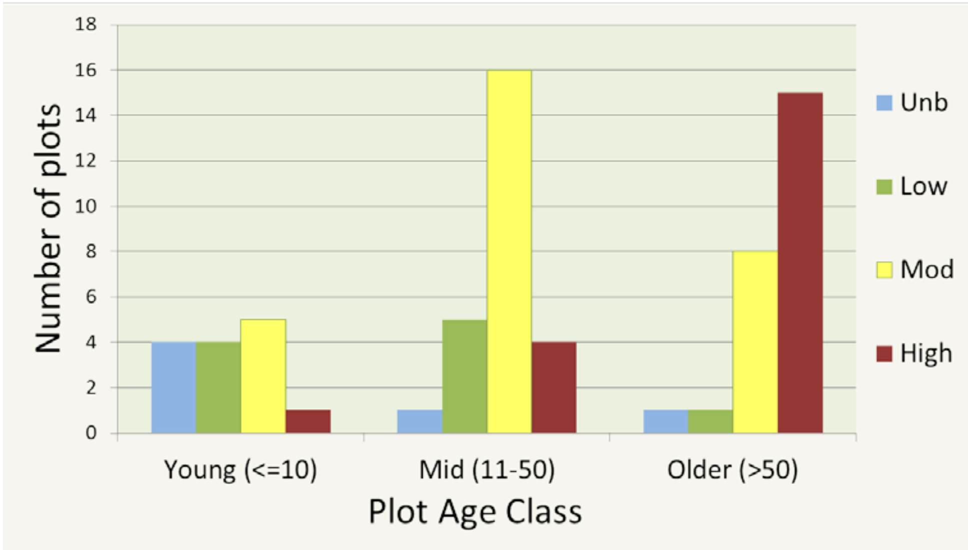
Thermal intensity-fuel consumption: Chaparral biomass was estimated from a combination of (1) post-fire measurement of the basal area of remaining shrub stems from 127, circular, 1/250-acre plots that were distributed in the area of active fire runs as observed by remote sensing with the FireMapper, (2) scaling relationships of biomass components to basal area for shrubs prior to burning and at different ages and for several species, and (3) correlation of pre-fire stand biomass estimates to broader averages of vegetation reflectance derived from TM imagery. Relations of pre-fire fuel biomass components to stem basal area were obtained from measurements in the vicinity of the Esperanza Fire by C. Wright (JFSP 03-1-3-06) and earlier measurements in 55-year-old chaparral by J. Regelbrugge (Ottmar et al. 2000). Stand biomass estimates followed the approach previously described, for example, by Riggan et al. (1988), Schlesinger and Gill (1980), and Conard and Regelbrugge (1993).

The fine live biomass (B_f) estimated for the 4.6-meter-diameter field plots showed, on a plot by plot basis, little correspondence to pre-fire estimates of the normalized difference vegetation index (NDVI), (nIR-red)/(nIR+red) reflectances, as determined from 30-m TM data collected in either February or June 2006 (prefire Landsat imagery). Averaging plot biomass and NDVI values by four ranges of ages and north and south aspects produced a good power function regression for ln (B_f). Large differences in scale and uncertainty in location between the small field plots and much larger TM pixels obscured a large-scale relationship between the reflectance and vegetation measurements. Available data also showed that the ratio of fine live woody biomass to foliage biomass was very similar between 10- and 55-year-old stands. The relationship for dead woody biomass was similar and low in young *Arctostaphylos glandulosa* and chamise but substantially higher at age 55 for either species.

Fuel loading showed a general correspondence with remotely observed fire irradiance. The Landsat NDVI measure showed skill in predicting broad classes of fuel accumulation and fire properties, yet sampling limitations precluded a more detailed analysis based on stand species composition and led to extrapolations at higher apparent biomass loading at higher elevations and low fuel loading in frequently burned and degraded landscapes.

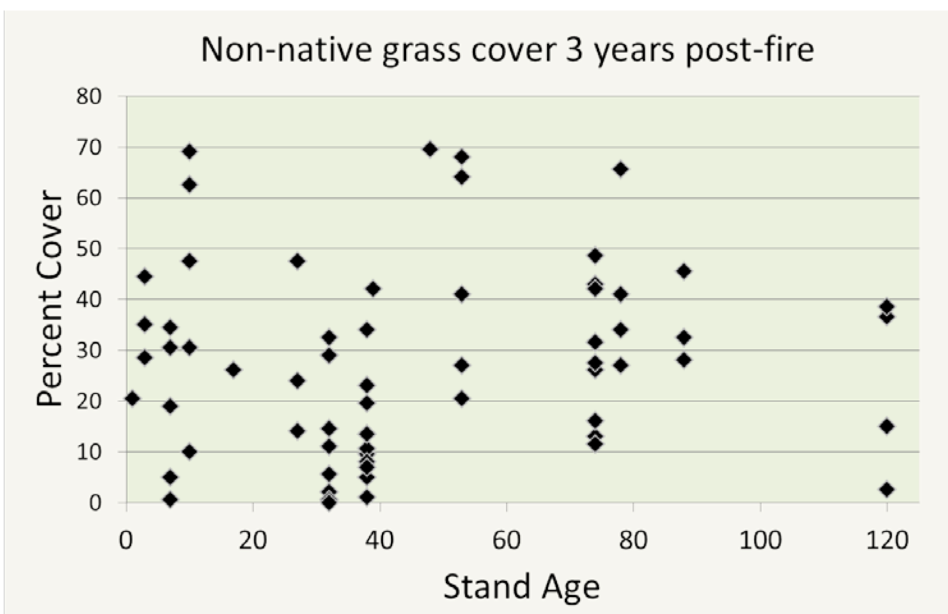
Post-fire vegetation recovery: Fourteen of the 65 sample points used for vegetation analysis had burned 10 or fewer years prior to the Esperanza fire ("young" stands). Most of these young stands had experienced 2 or 3 previous fires, confounding separation of recent and multiple fire effects. Twenty-four points contained intermediate-aged vegetation (11-50 years old at the time of Esperanza fire; "mid-age" stands), and the rest (27 points) burned more than 50 years earlier, including six with no recorded fire history (at least 100 years) ("older" stands). High fire severity, as characterized based on ground measurement, was found most frequently in older stands, with young stands often rated low or moderate severity (Figure 3).

Figure 3. Sample plot fire severity, as determined by ground measurements, of sample plots in three general age classes (years since previous fire) of pre-fire vegetation. "Unb" = unburned by Esperanza fire.



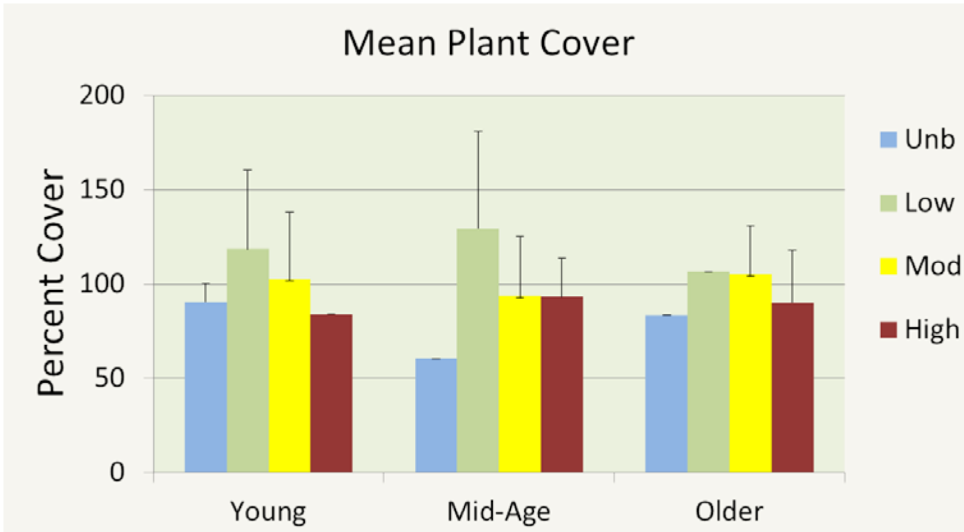
By 3 years post-fire, non-native grasses were common in plots of all ages (Figure 4); however, non-native grass and shrub cover were inversely related (data not shown). There was a wide range of non-native cover on the plots. We attempted to correlate non-native species cover to distance from the fuel break system, which would have provided a ready seed source, but preliminary analysis did not reveal a clear relationship.

Figure 4. Percent cover of non-native grasses by stand age measured 3 years after the Esperanza fire. The most abundant non-native grass species were cheatgrass (*Bromus tectorum*), red brome (*Bromus madritensis* ssp. *rubens*), and foxtail fescue (*Festuca myuros*).



Species richness tended to be highest in mid-aged plots, but plots of all ages had similar total plant cover 3 years after fire (Figure 5).

Figure 5. Plant cover by stand age class and fire severity (the latter as measured by ground crews) 3 years after the Esperanza fire. Overlapping canopies of individual species could add up to total cover greater than 100% on some quadrats. "Unb" = unburned by Esperanza fire.



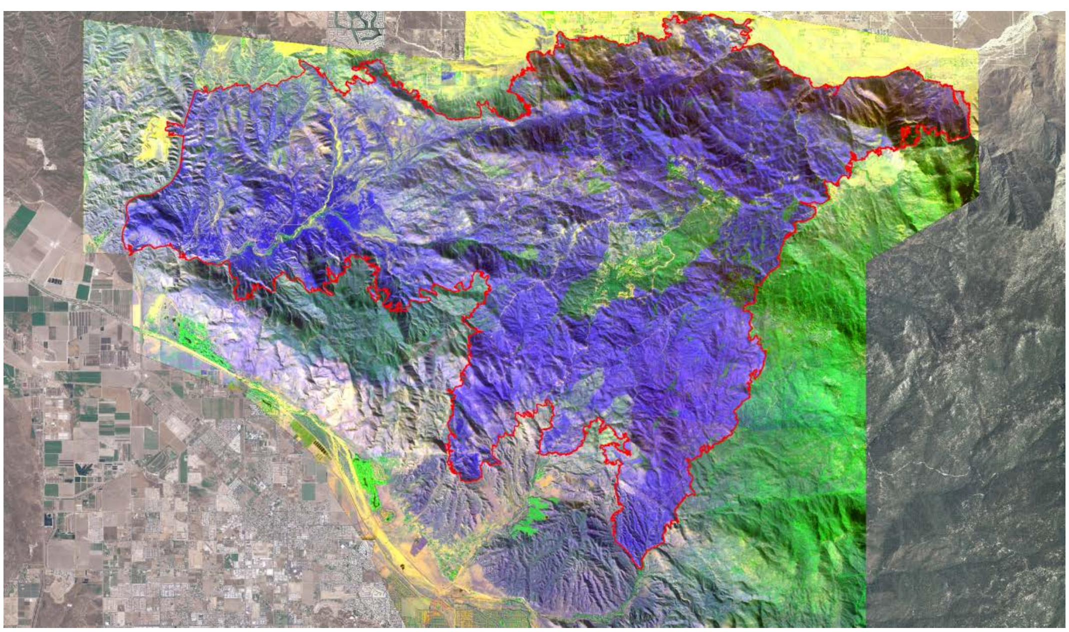
Soil seed bank composition in relation to stand age and fire severity: Fifty-nine species were identified as emerging from the soil seed bank samples, mostly native species typically found after fire in chaparral ecosystems. Seedling density ranged from 15 to several hundred produced from each 78 cm^2 area sample. Non-native grass seeds (mainly red brome, *Bromus madritensis* ssp. *rubens*, and cheatgrass, *B. tectorum*) were present most often in younger samples, but a few were found in the oldest samples as well. Samples from high intensity burn points (as determined by the ground-sampling crew) were dominated by fire followers such as *Phacelia brachyloba* and *Camissonia* species. Despite the presence within the NMEA of long-term fuel breaks, which were dominated by non-native grasses and burned lightly if at all during the Esperanza fire, very few seed bank samples contained substantial numbers of non-native seeds. The surviving seed bank appeared adequate to revegetate all areas of the fire, and this conclusion was borne out by the results of the vegetation sampling conducted in subsequent years (see previous section). Interestingly, more species germinated in the greenhouse than were observed in field vegetation measurements. Because we sampled vegetation after many early-germinating herbaceous species may have already matured, especially during 2008, we probably many missed small-statured early-senescing annual plants in the field.

Fuel breaks and non-native species spread: We expected to see greater cover of common non-native species, especially grasses, farther from fuel break edges the second year postfire. Fourteen of the fuel break transects fell within areas burned by the Esperanza fire, while 16 were unburned. Cover of non-native grasses, predominantly the bromes (*Bromus* spp.) and foxtail fescue (*Festuca myuros*), increased from the first to second year after fire in burned fuel breaks and adjacent vegetation; however, variability was high. Many of the transects that didn't burn in the Esperanza fire had burned one year earlier in the Soboba fire, and grass cover tended to be higher on those plots. Shrub cover increased from one to two years post-fire. Overall, non-native species expansion into burned chaparral was not as dramatic as we expected. At the same time, only minor colonization of the fuel breaks by chaparral shrubs occurred. The infrequently-maintained fuel breaks at North Mountain appear highly stable.

Utility of FireMapper for post-fire vegetation assessment: Flights during 2006, 2008, 2009, and 2011 documented the appearance of the post-fire landscape and changes with vegetation recovery in reflectance of red, near-infrared and short-wave infrared light and in radiometric temperature. Immediate post-fire imagery compared to estimates of fire severity based on remnant vegetation showed visible differences in fuel loading in the FireMapper images (Figure 6).

Trends in vegetation recovery were also tracked in sequential FireMapper images. The vegetation sampling protocol produced average cover values by species for the individual 400 m^2 sample plots, based on point hits totaled for the plots, but these values were initially hard to relate to the almost 1 m resolution of the FireMapper images from 2008 and 2009. Consequently, in 2011, sixteen plots were selected to re-sample groundcover along five evenly spaced 20 m line-intercept transects to give more spatially-precise species locations and cover values. Higher accuracy was obtained for plot locations and sampling transects when multiple sets of GPS collected coordinates were averaged. Using these data, plant species could be differentiated to some extent in the FireMapper color composite images: in image scatter grams of red vs. near-infrared values, FireMapper images of plots that contained an abundance of broad leaf species (manzanita and oak) clustered separately from plots in which chamise (a small leaf species) was predominant. General chaparral species categories can now be delineated using FireMapper multi-spectral imagery. Non-plant material of individual landscape features, such as soil and rock, could also be identified with FireMapper.

Figure 6. Color composite imagery of the immediate postfire environment of the Esperanza Fire, as viewed 28 October 2006, by the FireMapper imaging system. Reflected red light is mapped in red, reflected near-infrared light is mapped in green, and radiometric temperatures estimated from measured thermal-infrared radiation is mapped in blue. Bright bare ground of washes, fuel breaks, and roads appears yellow; unburned vegetation has shades from dull purple to green; and black ash appears blue or magenta. Brighter shades of green in unburned vegetation are correlated with heavier biomass loads. Unburned, dormant vegetation, including coastal sage and grasses, appears as a dull purple, as present on steep slopes south of the fire. The fire perimeter is shown in red.



V. Management Implications

The fuels and fire behavior analysis reiterate that chaparral fuel beds are much more complex than originally modeled by Albini (1976) using a single fuel model. This work confirms the importance of stand age and elevation on fuel loading in chaparral. Rothermel and Philpot (1973) proposed two dynamic fuel models for chaparral that were functions of age; these were made available for fire prediction in FIRECAST (Cohen 1986). Ottmar et al. (2000) and Scott and Burgan (2005) provide a wider range of fuel data and fuel models which managers should consider using as they develop fuel maps in chaparral and as they make fire spread predictions using current tools.

Short term differences were observed using sequential images from FireMapper. This technology can be useful for monitoring general recovery of vegetation after fire over time. Unique landscape features can be identified with FireMapper imagery and could be used to identify areas that may require resource management actions. On site verification of plant species relating to spectral images is highly recommended.

As in other studies, older stands generally exhibited highest fire severity in this wind-driven event: fuel volume matters. However, because by 3 years post-fire stands of all ages had similar total plant cover, "senescence risk" (Zedler 1995) was not apparent at this site, and high fire severity will not affect long-term stand recovery. NMEA is crisscrossed with historic fuel breaks dominated by herbaceous plants, mostly non-native species. Non-native grasses and forbs colonized all stand ages and severities by year 3 post-fire, illustrating that if a seed source is nearby, non-native species will readily invade burned chaparral. Grass invasion after fire was probably higher at NMEA than it would be in less fragmented stands of southern California chaparral. Risk of future fires will remain elevated until the grass is shaded out. Plots near the western edge of the fire, an area that had burned only a year earlier, are likely to be type-converted to mostly non-native annual grass and forb cover.

VI. Relationship to Other Recent Findings

The fuels information developed as part of this study and the relationships between the remotely-sensed energy-release and fuels information are being utilized in the modeling work being performed by Janice Coen on the WRF-FIRE and CAWFE integrated fire behavior-meteorological models. Preliminary results were reported in deliverables Coen et al. (2010) and Riggan et al. (2010). Further development of WRF-FIRE is reported in Coen et al. (in press), and future simulation work will model the Esperanza Fire spread. The remote-sensing relationships could potentially be used to estimate fuel consumption on the Troy Fire which is unique in that we have remotely-sensed fire perimeters of the entire fire with a time step of roughly 15 minutes between successive perimeters. The fuels data which was contributed to this project continues to be used as part of the "Fire behavior in live fuels" National Fire Plan project led by co-PI Weise.

Wildland susceptibility to non-native plant invasion has become a chronic problem worldwide (D'Antonio and Vitusek 1992). This often results in type conversion to fuels that increase fire frequency. High cover of non-native grasses in the third year post-fire measured in this study illustrates the potential susceptibility of young chaparral to fire (Keeley et al. 2005a).

Keeley et al. (2008) suggested there was a critical need for further research interpreting remote sensing indices as applied to post-fire management of California shrublands. Our work has advanced and refined the use of this technology as suggested by Lentile et al. (2006).

VII. Future Work Needed

The fuel consumption-remotely measured fire intensity relationship developed for chaparral in the area of the Esperanza Fire must be considered preliminary. While other work has described fuel consumption in chaparral, actual linkage with energy release measurements in real time at field scale has seldom been performed. An RX-CADRE scale study is needed in chaparral and other fire-prone western shrublands in order to better quantify the numerous variables associated with fuels, fire behavior, meteorology, smoke production and transport.

Further refinement is needed for spectral identification of landscape features linking them to FireMapper images. Spatially-explicit measurements of vegetation composition and non-vegetative features in additional post-fire environments would allow further calibration of spectral signals, eventually allowing vegetation development trends to be deduced from imagery alone.

The young chaparral stands that burned in the Esperanza fire are most likely to undergo type conversion, especially those only 1 to 3 years old in 2006. Most had burned 10 years earlier, which appeared to be long enough for a decent chaparral seed bank to have accumulated in the soil, and initial regrowth was dominated by chaparral species. Nonetheless, it could be instructive to remeasure those plots in another few years and compare them to plots which were in the "old" age classes at the time of the Esperanza fire as an indicator of the resilience of southern California chamise chaparral to a fairly short interval reburn.

VIII. Deliverables Cross-Walk

Table 2. Deliverables, Description, Delivery Dates, and Status

Deliverable	Description	Delivery Dates	Status
Conference presentation – Fire and Forest Meteorology symposium	Fuel consumption and remotely sensed fire intensity in chaparral	Fall 2007	Completed
Conference presentations Technical bulletin	Preliminary findings on post-fire vegetation response.	Winter 2008	2 posters at conferences in 2008, 3 in 2009, 1 in 2010, 1 in 2011
Tour of NMEA & workshop	Half day presentations at RFL and half day field tour	Late Spring 2008 and 2009	Not conducted
Conference presentations	Preliminary findings on post-fire seed bank to various thermal zone images taken during the Esperanza fire.	Summer or Fall 2008	2 posters at conferences in 2008, 1 in 2010
Journal article; technical bulletin	Fuel consumption and remotely sensed fire intensity in chaparral	Summer 2008	Included in 1 paper and oral presentation (2010)
Data on PSW web page	Electronic publication of data on FireMapper website	Winter 08 and continuing	
Journal articles Technical bulletins for managers	Correlations between fire severity observations and seed bank species diversity and abundance; analyzing vegetation response to fire using FireMapper	Fall 2009 – Spring/summer 2010	Poster presentations made; further data analysis under way

Deliverables Completed to Date:

Publications

Weise, D.R.; Riggan, P.J. 2007. Correlation between remotely sensed fire intensity and fuel consumption in California chaparral -- a case study. Extended abstract P1.5. 7th Symposium on Fire and Forest Meteorology, Oct. 22-25, 2007, Bar Harbor, Maine. http://ams.confex.com/ams/pdfpapers/126871.pdf

Coen, J.L.; Riggan, P.J. 2010. A landscape-scale wildland fire study using a coupled weather-wildland fire model and airborne remote sensing. In Wade, D.D.; Robinson, M.L. (eds.) Proceedings of the 3rd Fire Behavior and Fuel Conference, Oct. 25-29,2010, Spokane, Washington, USA. International Association of Wildland Fire, Birmingham, Alabama, USA. 10 p. (CD publication)

Riggan, P.J.; Wolden, L.G.; Tissell, R.G.; Weise, D.R.; Coen, J. 2010. Remote sensing fire and fuels in southern California. In Wade, D.D.; Robinson, M.L. (eds.) Proceedings of the 3rd Fire Behavior and Fuel Conference, Oct. 25-29,2010, Spokane, Washington, USA. International Association of Wildland Fire, Birmingham, Alabama, USA. 14 p. (CD publication)

Coen, J.; Cameron, M.; Michalakes, J.; Patton, E.; Riggan, P.; Yedinak, K.. (in press). WRF-Fire: Coupled Weather-Wildland Fire Modeling with the Weather Research and Forecasting Model. Journal of Applied Meteorology and Climatology. doi:10.1175/JAMCD-12-023.1, in press.

Beyers, J.L.; Narog, M.G.; Wrona, A.M. 2011. Do non-native species invade chaparral from fuel breaks after fire? Poster abstract In Wade, D.D.; Robinson, M.L. (eds.) Proceedings of the 3rd Fire Behavior and Fuel Conference, Oct. 25-29, 2010, Spokane, Washington, USA. International Association of Wildland Fire, Birmingham, Alabama, USA. 1 p.

Student Paper

Blue, Andrea and Cassandra Pardee. 2009. Postfire chaparral regrowth in fuel breaks. Senior capstone project, Biology Department, University of Redlands, Redlands, California. 28 p.

Oral Presentations

Narog, Marcia; Beyers, Jan; Riggan, Philip; Wolden, Lynn; and Weise, David. 2011. Flames, fuels, foliage, and FireMapper. Offered oral presentation at MEDECOS XII: Linking Science to Resource Management. The International Mediterranean Ecosystems Conference, September 6-9, 2011, Los Angeles, California.

Riggan, P.J.; Wolden, L.G.; Tissell, R.G.; Weise, D.R.; Coen, J. 2010. Remote sensing fire and fuels in southern California. 3rd Fire Behavior and Fuel Conference, Oct. 25-29, 2010, Spokane, Washington, USA.

Coen, J.L.; Riggan, P.J. 2010. A landscape-scale wildland fire study using a coupled weather-wildland fire model and airborne remote sensing. 3rd Fire Behavior and Fuel Conference, Oct. 25-29, 2010, Spokane, Washington, USA.

Poster Presentations

Weise, D.R., and P.J. Riggan. 2007. Correlation between remotely sensed fire intensity and fuel consumption in California chaparral -- a case study. 7th Symposium on Fire and Forest Meteorology, Oct. 22-25, 2007, Bar Harbor, Maine.

Paysen, T.E.; Narog, M.G.; Beyers, J.L.; Riggan, P.J.; Weise, D.R. 2008. Reduce high cost of fire with tools for landscape-scale resource evaluation. Poster presentation at III International Symposium on Fire

Economics, Planning and Policy: Common Problems and Approaches, April 29-May 2, 2008, Carolina, Puerto Rico.

Beyers, J.L.; Narog, M.G.; Paysen, T.E.; Weise, D.R.; Riggan, P.J. 2008. Fire severity and vegetation age class effects on post-fire chaparral seed banks. Offered poster presented at the 93rd annual meeting of the Ecological Society of America, August 3-8, 2008, Milwaukee, Wisconsin. Abstract online at: http://eco.confex.com/eco/2008/techprogram/P14799.HTM

Narog, M.G.; Beyers, J.L.; Paysen, T.E. 2008. Plant community diversity after fire along chaparral fuel breaks. Offered poster presented at the 93rd annual meeting of the Ecological Society of America, August 3-8, 2008, Milwaukee, Wisconsin. Abstract online at: http://eco.confex.com/eco/2008/techprogram/P14790.HTM .

Beyers, Jan L.; Narog, Marcia G.; Paysen, Timothy E.; Weise, David; Riggan, Philip. 2008. Fire severity and vegetation age class effects on post-fire chaparral seed banks. Offered poster presented at Pacific Coast Fire Conference: Changing fire regimes, goals and ecosystems, December 1-4, 2008, San Diego, California.

Parlow, Mark E.; Narog, Marcia G.; Beyers, Jan L.; Weise, David R.; Riggan, Philip J.; Wrona; Anna. 2009. Aerial thermal imagery and plant diversity in post-fire environments of the North Mountain Experimental Area. Offered poster presented at the Southern California Academy of Sciences annual meeting, May 29-30, 2009, Marymount College, Palos Verdes, California.

Wrona, Anna M., Marcia G. Narog, Tim Paysen, Jan L. Beyers. 2009. Effects of recent fire on plant diversity along chaparral fuel breaks. Offered poster presented at the Southern California Academy of Sciences annual meeting, May 29-30, 2009, Marymount College, Palos Verdes, California.

Beyers, J.L.; Narog, M.G.; Wrona, A.M. 2011. Do non-native species invade chaparral from fuel breaks after fire? 3rd Fire Behavior and Fuel Conference, Oct. 25-29, 2010, Spokane, Washington, USA.

Narog, Marcia. 2010. Esperanza's post-fire seed bank. Offered poster (PS 51-53) at Annual Meeting of the Ecological Society of America, 1-6 August 2010, Pittsburgh, Pennsylvania.

Narog, Marcia G.; Wolden, Lynn; Beyers, Jan L.; Riggan, Philip J. 2012. Fine-tuning FireMapper imagery for post-fire plant recovery. Offered poster presented at Annual Meeting of the Ecological Society of America, August 5-10, 2012, Portland, Oregon.

IX. Literature Cited

Albini, F.A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Blandford, R.H. 1962. The North Mountain project of land treatment for fire protection. State of California, The Resources Agency, Department of Conservation, Division of Forestry, Sacramento 14. 17 pp.

Cohen, J.D. 1986. Estimating fire behavior with FIRECAST: user's manual. Gen. Tech. Rep. PSW-90. Berkeley, CA: USDA Forest Service Pacific Southwest Forest and Range Experiment Station. 11 p.

Conard S.G., and J.C. Regelbrugge. 1993. On estimating fuel characteristics in California chaparral. In: Proceedings of the 12th Conference on Fire and Forest Meteorology, October 26-28, 1993, Jekyll Island, Georgia. Bethesda, MD: Society of American Foresters; 120-129.

D'Antonio, C.M., and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23: 63-87.

Keeley, J.E. 2006. Fire management impacts on invasive plants in the western United States. Conservation Biology 20: 375–384.

Keeley, J.E., M. Baer-Keeley, and C.J. Fotheringham. 2005a. Alien plant dynamics following fire in Mediterranean-climate California shrublands. Ecological Applications 15(6): 2109-2125.

Keeley, J.E., T. Brennan, and A.H. Pfaff. 2008. Fire severity and ecosystem responses following crown fires in California shrublands. Ecological Applications 18(6): 1530-1546.

Keeley, J.E., and C.J. Fotheringham. 2001a. Historic fire regime in southern California. Conservation Biology 15: 1536-1548.

Keeley, J.E., and C.J. Fotheringham. 2001b. History and management of crown-fire ecosystems: A summary and response. Conservation Biology 15: 1561-1567.

Keeley, J.E., C.J. Fotheringham, and M. Baer-Keeley. 2005b. Factors affecting plant diversity during post-fire recovery and succession of Mediterranean-climate shrublands in California, USA. Diversity and Distributions 11: 525-537.

Keeley, J.E., C.J. Fotheringham and M. Baer-Keeley. 2005c. Determinants of postfire recovery and succession in Mediterranean-climate shrublands of California. Ecological Applications 15(5): 1515-1534.

Lentile, L.B., Z.A. Holden, A.M.S. Smith, M.J. Falkowsik, A.T. Hudak, P. Morgan, S.A. Lewis, P.E. Gessler and N.C. Benson. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire 15(3): 319-345.

Merriam, K.E., J.E. Keeley, and J.L. Beyers. 2006. Fuel breaks affect nonnative species abundance in Californian plant communities. Ecological Applications 16: 515-527.

Minnich, R.A. 2001. An integrated model of two fire regimes. Conservation Biology 15: 1549-1553.

Moritz, M.A, J.E Keeley, E.A Johnson, and A.A. Schaffner. 2004. Testing a basic assumption of shrubland fire management: How important is fuel age? Frontiers in Ecology and Environment 2: 67-72.

Ottmar, R.D., Vihnanek, R.E., and J.C. Regelbrugge. 2000. Stereo photo series for quantifying natural fuels - Vol. IV: pinyon-juniper, chaparral, and sagebrush types in the southwestern United States. PMS-833. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center.

Plumb, T.R., J. R. Bentley and V. E. White. 1963. Chemical control of brush regrowth on fuel-breaks. State of California Department of Conservation, Division of Forestry, Los Angeles County Fire Department, USDA Forest Service, Region 5, and PSW Forest and Range Experiment Station,. Fuel-break Report No. 11. 41 p.

Potts, J.B. and S. Stephens. 2009. Invasive and native plant responses to shrubland fuel reduction: comparing prescribed fire, mastication, and treatment season. Biological Conservation 142(8): 1657-1664.

Riggan, P.J., and J.W. Hoffman. 2003. FireMapper™: a thermal-imaging radiometer for wildfire research and operations. Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, Paper no. 1522.

Riggan, P. J., R. G. Tissell, and J.W. Hoffman. 2003. Application of the FireMapper® thermal-imaging radiometer for fire suppression. Proceedings from the 2003 IEEE Aerospace Conference, paper no. 1523, March 8-15, 2003.

Riggan, P.J., F.H. Weirich, L.F. DeBano, P.M. Jacks, R.N. Lockwood, C. Colver, and J.A. Brass. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. Environmental Science and Technology 28: 369–375.

Riggan P.J., S. Goode, P.M. Jacks, and R.N. Lockwood. 1988. Interaction of fire and community development in chaparral of southern California. Ecological Monographs 58(3): 155-176.

Rothermel, R.C., and C.W. Philpot. 1973. Predicting changes in chaparral flammability. Journal of Forestry 71(10): 640-643.

Schlesinger, W.H., and D.S. Gill. 1980. Biomass, production, and changes in the availability of light, water, and nutrients during the development of pure stands of the chaparral shrub, *Ceanothus megacarpus*, after fire. Ecology 61(14): 781-789.

Scott, J.H., and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Ft. Collins, CO: USDA Forest Service, Rocky Mountain Research Station.

Stephenson, J. R. and G. M. Calcarone. 1999. Southern California mountains and foothills assessment: Habitat and species conservation issues. General Technical Report GTR-PSW-172. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA. 402 p.

Zedler, P.H. 1995. Fire frequency in southern California shrublands: Biological effects and management options. In Keeley, J.E. and T. Scott (eds.), Brushfires in California wildlands: Ecology and resource management. Fairfield, WA: International Association of Wildland Fire; 101-112.