Evaluation of Wildfire Mapping with NOAA/AVHRR Data by Land Cover Types and Eco-Regions in California

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Abstract

In order to determine the efficacy of archived remotely sensed data to create historic fire maps, this study compares a remote sensing based wildland fire map with an historical fire database for California, USA. Fires occurring in two years (1996 and 1999) were mapped using data obtained from the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensor. A vector database of fire perimeters, compiled and maintained by the State of California was obtained as a source of comparison for the AVHRR based fire map. The two datasets were overlaid and spatially compared in seven land cover types and ten ecoregions. The sources of disagreement and overlap between the datasets were quantified in order to elucidate trends in fire detection algorithm performance over the land cover types and ecoregions. Various methods of vector based comparison were examined in order to more effectively describe the spatial relationships between the two fire maps. The results show that algorithm performance varies over both ecosystem type and geographic region of California. The remote sensing method was able to map between 62% and 74% (1999 and 1996, respectively) of fire area mapped in the State maintained database. There was between 40% and 45% (1999 and 1996, respectively) of geographic overlap in the datasets. The results illustrate the need to calibrate remotely sensed algorithms by ecosystem type and geographic location in order to more effectively produce historic fire map products for research and other purposes.

I. INTRODUCTION

Wildland fire occurs on a large scale in California, USA, resulting in extensive annual ecosystem change (Sandberg et al., 2002). Wildland fire effects include a potentially significant localized disturbance, local, regional and continental impacts, and plumes of "smoke" (particulate emissions) visible from space (Lee et al., 2003; Fearnside, 2000; Wotowa and Trainer 2000; Davies and Unam 1999; Conrad and Ivanova, 1997). Single fire events in California may result in excess of 40,000 hectares (100,000 acres) of burned area. These large scale disturbances are linked to global processes of climate change through the direct contribution of emissions to the atmosphere and carbon fertilization effects that contribute to the development of "fuels" that burn (Dale et al., 2001). The impacts of wildland fire on carbon cycles and storage are compounding. Carbon that was sequestered in vegetation (especially forests), is immediately converted to emissions (particulates, gasses, and aerosols), the vegetation that previously occupied the site is taken out of photosynthetic "production," and the decomposition of rooting systems can cause the soil to become a source of carbon dioxide (National Research Council, 2003).

The interaction between terrestrial disturbances and climate can be studied through the examination of historic relationships between burned areas and climatic factors. These relationships may be evidenced by spatial correlations between vegetation conditions, weather regimes, other disturbances, and the location of wildland fires. The first stage in such an examination is the creation of an historic burned area map. This study describes the efficacy of a remote sensing approach for building historic maps of fire occurrence using the NOAA Advanced Very High Resolution Radiometer (AVHRR).

AVHRR (onboard the NOAA-14 satellite and earlier) data are available at a nominal resolution of 1.1 km in five channels: the visible, near-infrared (IR), mid-IR and two thermal-IR portions of the spectrum. Such spectral resolution offers considerable benefits to fire monitoring (Harris, 1996). Channels 1 and 2 provide data capable of detecting, monitoring and measuring smoke emissions (Khazenie and Richardson, 1993; Kaufman et al., 1990), but contain no thermal information. Channel 3 is extremely sensitive to sub-pixel hot spots, making it the most important channel for fire detection (Rauste et al., 1997; Pozo et al., 1997) though it has a low temperature saturation point (~321 k) (most existing algorithms concentrate on the third channel, hoping to overcome this disadvantage). Channels 4 and 5 are far less sensitive to sub-pixel hotspots, but they can frequently help detect fires when combined with other channels (Flasse and Ceccato, 1996; Justice et al., 1996). In addition, the AVHRR onboard post-NOAA-14 satellite also includes a 1.65 μm short wave infrared (SWIR) channel. The SWIR channel has been proven highly effective in discriminating burned boreal forest (e.g., Fraser and Li, 2002). Recently, MODIS (the MODerate resolution Imaging Spectroradiometer, onboard EOS series satellites) imagery has become another source of data of appropriate spatial and temporal resolution to be used for global studies of biomass burning (Kaufman et al., 1998). However, if focusing on the study of historical

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burned area detection and emission estimation before 2000, the archive AVHRR data are the data sources un-replaced with other data sets such as MODIS.

Using AVHRR, remote sensing of wildland fire has been tested in the Canadian boreal forest (Fraser et al., 2000), Alaskan boreal forest (Bourgeau-Chavez et al., 1997), Spanish Mediterranean ecosystems (Al-Rawi et al., 2001) and other regions (Chuvieco and Martin, 1994). Other sensors employed for mapping wildfires include SPOT High Resolution Visible and InfraRed (HRVIR) in the tropics (Phulpin et al., 2002), Landsat Thematic Mapper (TM) in Thailand (Giri and Shrestha, 2000), the Bi-spectral InfraRed Detection small satellite (BIRD) in Australia (Wooster et al., 2003), Tropical Rainfall Measuring Mission Visible and InfraRed Scanner (TRMM VIRS) in the tropics (Giglio et al., 2000), and Moderate Resolution Imaging Spectroradiometer (MODIS) in Africa (Justice et al., 2002).

A variety of methods have been employed in the comparison of remote sensing results to ground based fire area surveys. Bourgeau-Chavez et al. (1997) reported percent fire area detected for each fire (using both AVHRR and a radar imager aboard European Remote-Sensing Satellite ERS-1), and as an aggregate of all burn areas for fires that were "detected." Fires not detected were excluded from the analysis. Al Rawi et al. (2001) and Li et al. (2000) take a raster (pixel) based percentage approaches. These studies reported percentage of pixels inside and outside ground survey data. Fraser et al. (2000) performed a regression of remotely sensed burn areas with areas from a ground based survey of wildfires, showing a strong relationship between the fire sizes measured *in situ* and the remotely sensed fire sizes. Remmel and Perera (2001) generated more elaborate "accuracy metrics." Through these metrics, not unexpected issues with positional uncertainty and "false" detection were revealed.

Percentage of area detected ranges from 31% (Remmel and Perera, 2001) to 100% (Al-Rawi et al., 2001), depending on sample size. Accuracy can be improved by restricting the sample to several large fires. Previous studies have validated the remote sensing of fires in relatively homogenous land cover types (e.g., boreal forest, Fraser et al., 2000; Li et al., 2000; Remmel and Perera, 2000; Borgeau-Chavez et al., 1997), over small areas (Al-Rawi et al., 2001), or in relation to other satellite data (Wooster et al., 2003; Justice et al., 2002; Phulpin et al., 2002). In this study, the Center for the Assessment and Monitoring of Forest and Environmental Resources (CAMFER) at the University of California at Berkeley applied a wildland fire detection algorithm (the CAMFER algorithm, modified from Li et al. (2000) for hotspot detection and Fraser et al. (2000) for burn scar mapping) to a wide variety of land cover and ecosystem types across the state of California using AVHRR data. The objective of this study was to compare the performance of a consistent algorithm across eco-regional and eco-systematic boundaries and elucidate differences in the way fires are detected and mapped in different natural landscapes. We quantify the observed differences in map accuracy over different ecosystems and regions in order to determine the level of confidence with which fires can be mapped in different natural environments. The broad scale application of remote sensing algorithms for fire detection at continental or even global scales can benefit from this type of ecological validation and investigation. In that context, this paper aims to describe fire mapping results not only in terms of overall accuracy, but also in terms of divergent detection rates as they relate to on the ground differences in vegetation and land cover.

II. MAPPING AREA AND DATASETS

The California landscape represents an extensive set of ecological conditions in which to test a remote sensing approach to fire detection and mapping. There exists within the state boundary moist and cool coastal forest, nearly barren desert, urban area, high elevation forest, grassland, savannah, woodland, chaparral and nearly every conceivable combination of these systems (Barbour et al., 1993). For these reasons, California was deliberately chosen as a testing area for remote sensing based fire mapping using AVHRR.

We obtained a vegetation coverage, and Jepson Ecoregion coverage (Davis et al., 1998) as polygons, from the California GAP analysis project (See Figure 1). These maps, like much of the spatial data maintained by State of California, are in the Teale Albers projection. For the purposes of this study, we generalized the vegetation coverage to the following categories, based on the original Holland (1986) classification: open land, dunes, scrub, grassland, wetland, riparian, woodland, forest. The ecoregions were already suitably broad and did not require any modification.

The California Department of Forestry and Fire Protection (CDF) compiles a geographic database of fire occurrence. The CDF Fire Perimeter coverage (Arc/Info regions in Teale Albers projection) contains digitized fire boundaries (as polygons) collected from the State and Federal agencies responsible for land management in California. A complete description of this database is found at http://frap.cdf.ca.gov/projects/fire_data/fire_perimeters/methods.asp (last viewed 7/18/2003). However, for the purposes of this study, it is important to note that the CDF coverage is not perfectly reliable.

The CDF website describes the fire perimeter coverage as follows: "The fire perimeter database represents the most complete digital record of fire perimeters in California. However it is still incomplete in many respects." The CDF fire coverage is constrained by data availability at the multiple agencies that contribute to the database and is therefore only as complete as the fire records that were kept by the contributing agencies. As an example, CDF, the agency responsible for fire mapping on private lands in California, only entered fires 300 acres or larger into the database. The federal cutoff for fire mapping is 10 acres. The fires were entered into the database

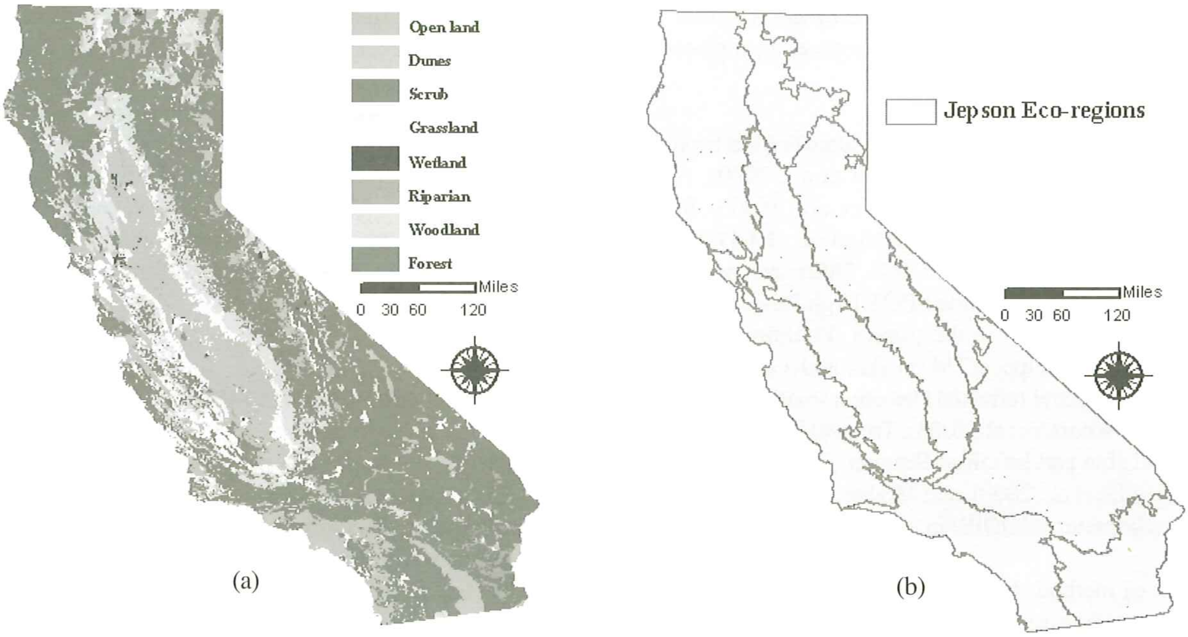

Figure 1. Polygon coverages obtained from the California GAP project. (a) shows landcover generalized from detailed vegetation polygons; (b) shows Jepson ecoregions. We used these data to allocate fires by landcover and ecoregion.

in a variety of ways, including digitization from paper maps. Horizontal accuracy is not reported.

The creation of burn area maps that span decades or more is stymied by the difficulty or impossibility of ground based verification of fires from previous years. While some burn areas may be evident for many years, the rapid re-vegetation of other burn areas can quickly erase any visual clues as to the precise location of the fire. Attempts to find and record (with GPS or other survey technology) the boundaries of fires that burned ten or more years ago may be completely futile. For these reasons, the creation of a true and comprehensive historic burn area map is difficult, especially over a large geographic area managed by multiple agencies. The CDF fire database, as the most complete record of historic fires available, was used as a comparison to remotely sensed burn area maps created in the CAMFER.

III. METHODS

Wildfire mapping with AVHRR data.

CAMFER applied the integrated approach to wildfire mapping with the daily AVHRR data. The approach consists of two stages: active fire detection and burnt area mapping. For active fire detection, we combined the strengths of a fixed multi-channel threshold algorithm and an adaptive-threshold contextual algorithm and modified the fire detection algorithm developed by Canadian Center for Remote Sensing (CCRS) for fire detection in boreal forest ecosystems. At the active fire detection stage, we first filtered out all possible active fires (hotspots) with AVHRR channel 3, then used a test chain (by combination of channels 2 – 5) to eliminate false alarms from the possible active fires to finally form an active fire mask used for burnt scar mapping at next stage. For burnt area mapping, we adopted the basic idea of the HANDS algorithm, which combines the strengths of hotspot detection and multi-temporal NDVI differencing. We modified the HANDS procedure to make it applicable to California and implemented it in PCI image processing package. At this stage, we first used mean and standard deviation (SD) of NDVI decrease to produce all potential burnt scars (PBS), then confirmed (grew) the PBS based on some criteria (e.g., a burnt scar must contain a certain proportion of hotspots) to output a burnt scar map. The threshold for NDVI decrease is dependent on the mean and SD of NDVI reduction over a subset of hotspots corresponding to major cover types in California: forest, grass (rangeland), shrub, woodland and riparian. The pre-defined threshold is determined by a constant times the SD plus mean of NDVI decrease within a cover type.

We collected daily NOAA-14/AVHRR HRPT (High Resolution Picture Transmission format) images and pre-processed them with PCI Geocomp-n software (PCI Geomatics Corporation, Canada). The original spatial resolution is 1.1 km at nadir and the entire imagery was re-sampled into 1 km after preprocessing. Due to cloudiness, the temporal range of the imagery was limited to May through October of 1999 and July through October of 1996. We chose these years for testing due to above average wildfire activity and the availability of CDF data for comparison. Using the algorithm described above, we produced binary burn area maps for California in 1996 and 1999 separately, using 10-day NDVI composites as before (1 calendar year earlier) and after (1999 or 1996 10-day composite at the end of the fire season) images for the NDVI differencing, and thresholds of 0.4 for 1999 and 0.25 for 1996, timing SD plus mean of NDVI decrease.

Fire map format conversion

We exported the burn area maps as Tiff images in the Lambert Conformal Conic projection, with 1 km resolution. In order to be compared with the other datasets, this native format needed to be converted to the Albers projection. With Arc/INFO and ArcView software, we converted the images to grids, and grouped the cells into areas of contiguous burn pixels. In this step, we assumed burn pixels to be part of the same fire event if they shared a non-diagonal boundary. We classified diagonal neighbors as separate fire events and assigned unique identification (id) numbers accordingly (this was necessary for topological reasons that would affect the data in vector format). Next, we converted the grids to polygons (vectorization of what was originally raster data) for ease of comparison, manipulation and re-projection. The polygons retained the id numbers originally assigned to the corresponding group of pixels. To facilitate overlay with other datasets, we re-projected the satellite fire data to Teale Albers.

These manipulations slightly distort the data from its native format. In order to retain pixel distribution patterns and avoid re-sampling, we converted raster-based data to vectors prior to re-projection. However, vector re-projection results in a slight alteration of area. This resulted in a minimum polygon size (the geographic remnant of what was once an one kilometer pixel) of slightly less than 100 hectares (one square kilometer), that deviated in size depending on geographic location. This effect necessitated a certain degree of caution with regard to overlay with other data. The uncertainty in positioning and shape resulting from the change in format and projection necessitated the use of comparison techniques insensitive to geographic drift of features.

Methods of Comparison

We analyzed the coincidence of the CDF and CAMFER maps through two methods of vector data comparison. The first method involves relaxed rules for agreement between the two coverages (See Figure 2). The area of intersection is not computed, but CDF and CAMFER fire polygons are considered to be "matching" if any part of them overlaps. This approach is designed to reduce the effects of registration error (in either CDF or the original AVHRR data) on the ultimate determination of fire detection effectiveness. It also approximates an interpretation of the map comparison on a fire-by-fire basis, in terms of matching acreages, rather than a pixel based or intersection based approach. We call this the "hit-or-miss" method.

The second approach involves a geographic union of the CDF fire polygons and the CAMFER fire polygons derived from the original, raster-based data (See Figure 3). This union, performed in Arc/INFO, results in the splitting of polygons (when overlapping) according to whether they a.) enclose area coinciding to *both* CDF and the CAMFER map (intersection), i.e. area of the CDF coverage detected by the remote sensing approach, b.) enclose area exclusive to the CDF coverage, i.e. lack of detection, or c.) enclose area exclusive to the remote sensing data, i.e. CAMFER fires that do not have corresponding polygons in the CDF polygon coverage. With this approach, we tracked the precise areas of agreement and disagreement between the two layers. We call this the "intersection" method.

We evaluated how the two fire coverages compared in each Jepson ecoregion and each land cover type. The polygons are allocated to cover type and ecoregion by their centroids. We created centroids for each fire and each polygon resulting from the union of coverages and determined fire membership to cover type or ecoregion according to where the centroid (center of mass) was located. Since single fires may be decomposed into numerous overlapping and non-overlapping

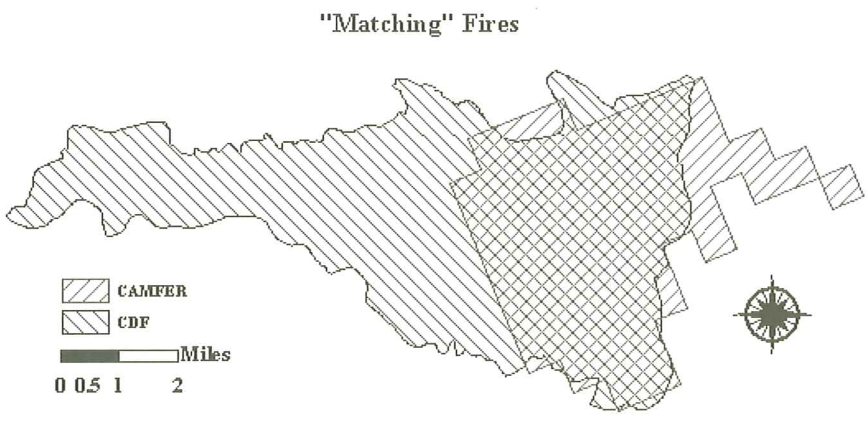

Figure 2. The hit-or-miss method. In this comparison, the intersecting area is not calculated. The entire area of each "fire" is considered to be "matching." This approach is designed to assess the map accuracy on a per fire basis.

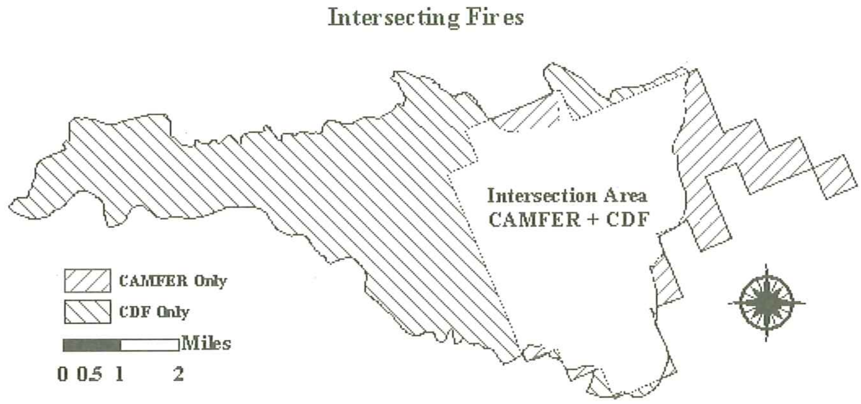

Figure 3. The Intersection method. The open section represents the intersecting are of a fire polygon from the CDF database and a fire polygon (mapped burn scar) generated with the CAMFER algorithm from AVHRR data.

areas through the union, the centroid based allocation is more geographically specific with the intersection approach than with the hit-or-miss approach. The assignment of ecoregional and land cover membership enabled us to assess the level of agreement between the coverages for each geographic zone. We added the areas of intersection, CDF fire area, and CAMFER fire area to produce statistics for the ecoregions and land covers.

IV. RESULTS AND ANALYSIS

Table 1 shows the total acreage of fires in the CDF database and the CAMFER maps, in each ecoregion and cover type, for 1999 and 1996. This includes fires in the CDF database outside the weather induced window of RS (remote sensing) data availability (May to October for 1999 and July to October for 1996). These fires are included for the purpose of judging the efficacy of a remote sensing approach to produce an annual burn map. Since portions of the year are characterized by cloudiness that obscures the imagery, this constraint is built in to the comparison. In 1999, 56 fires in the CDF database, accounting for 23,984 acres, are listed as occurring prior to May or after October. However in 1996, 88 fires accounting for 68,448 acres are listed before July and (3 fires) after October.

Table 1. The total acreage mapped by the remote sensing technique (CAMFER fires) and as it appears in the CDF database of fire perimeters (CDF fires). The data is summarized by its location in regard to the Jepson Eco-regions and land cover types (Figure 1).

	1999		1996	
Eco-Region	CDF Fires	CAMFER Fires	CDF Fires	CAMFER Fires
Cascade Ranges	159,094	40,406	3,707	1,831
Central Western California	123,630	240,339	148,986	102,681
East of Sierra Nevada	4,051	3,547	924	22,841
Great Central Valley	13,382	14,887	37,391	5,754
Modoc Plateau	36,322	9,649	32,719	64,000
Mojave Desert	5,860	30,606	13,578	77,620
Northwestern California	210,452	183,835	109,331	98,780
Sierra Nevada	106,928	36,950	152,409	74,802
Sonoran Desert	5,150	5,183	2,204	6,025
Southwestern California	115,837	94,083	135,664	70,596
Total	**780,706**	**659,485**	**636,913**	**524,930**
Land Cover				
Forest	301,831	180,167	153,390	173,558
Grassland	24,585	52,261	78,807	9,473
Open land	5,795	2,814	5,040	3,229
Riparian	55	3,113	1,160	0
Scrub	235,361	271,452	297,906	274,890
Wetland	0	0	611	5,976
Woodland	213,079	149,678	99,999	57,804
Total	**780,706**	**659,485**	**636,913**	**524,930**

It is notable that 51 of the 88 fires, totaling 40,984 acres occur in June of 1996. Meaningful temporal analysis based on these date attributes is confounded by the fact that the CDF database also contains nonsensical data such as a 'month' value greater than '12' or equal to '0.' In 1999, these nonsense months account for 68 fires and 200,835 acres in the CDF database. In 1996, the non-data are present in the records for 65 fires, amounting to 202,871 acres. Our ability to narrow the temporal range of the comparison is restricted by this lack of information in the CDF dataset.

The data in Table 1 show that the total CAMFER acreage for both years is lower than the acreage indicated by the CDF database. This is due in part to the availability of imagery in the early and late parts of the fire season, but is also likely to result from underestimation and lack of detection. Interestingly, there is a consistent underestimate in the Sierra Nevada region and the Northwest region of California, both largely forested areas. Underestimates of Woodland fire are also characteristic of both years.

Table 2 shows the acreage of "matching" fires, according to the hit-or-miss method of comparison. These data show the acres of fires that are mapped in approximately the same place, enough to overlap over all or part of the fire polygon. In both years, the Forest and Scrub ecosystems are the most significant, in terms of acreage of matched fires. These ecosystems are clearly predominant in terms of where fires are mapped and matched in both CDF and CAMFER fire maps. The trend of over or under estimation differs between the years, with woodland being the only consistently cover type shown to be consistently underestimated by a remote sensing approach.

The intersection method indicates the distribution of detected (CDF and CAMFER), undetected (CDF) and non-intersecting (CAMFER) area by cover type and eco-region. Table 3 shows the relative amounts of CDF fires that intersect with CAMFER fires. Table 4 shows percentage of detection success by cover type. This percentage is defined as [area of intersection] / [area of intersection + area of undetected CDF fire polygons]. This includes whole fires undetected by the CAMFER algorithm (due in part to fires outside the temporal range of the RS input data) and parts of fires not overlaid by the CAMFER fire map. In both 1999 and 1996, the forest cover type is the most effectively detected and in 1999 represents by far the most acreage of any ecosystem to be positively identified as burn area. In 1996, however, the detection percentage is slightly higher for scrub ecosystems. Grassland is the most difficult system in which to accurately map fires with massive underestimates in 1996 and a large area of fires in 1999 that do not match anything in the CDF database.

Table 2. Matched acreage (calculated with the hit-or-miss method) for remotely sensed burn scars (CAMFER fires) and fires in the CDF database. The total acreage of all "matching" fires is added. Totals matches and the percent of all mapped area is shown at the bottom of the table.

	1999		1996	
Eco-Region	CDF Fires	CAMFER Fires	CDF Fires	CAMFER Fires
Cascade Ranges	113,586	40,406	1,848	1,372
Central Western California	112,303	187,688	132,867	97,704
East of Sierra Nevada	0	0	0	0
Great Central Valley	1,249	0	0	0
Modoc Plateau	5,063	4,620	24,154	17,494
Mojave Desert	0	12,835	7,180	4,879
Northwestern California	201,206	177,078	85,331	96,259
Sierra Nevada	59,069	33,670	90,829	72,427
Sonoran Desert	0	0	0	0
Southwestern California	85,974	65,968	51,526	29,957
Total	**578,450**	**522,265**	**393,735**	**320,092**
Land Cover				
Forest	255,078	172,221	119,059	170,190
Grassland	5,028	22,403	21,581	2,217
Open land	0	662	0	0
Riparian	0	0	0	0
Scrub	159,622	212,436	191,878	92,503
Wetland	0	0	0	0
Woodland	158,722	114,543	61,217	55,182
Total	**578,450**	**522,265**	**393,735**	**320,092**
Percent of Total Mapped Acres	**74%**	**79%**	**62%**	**61%**

Table 3. The results of a geographic union: the intersection method (see Figure 3). The area of intersection is represented by the "cdf+camfer" column. The area of CDF fires not overlaid by mapped burn scars is represented in the "cdf only" column and the area of burn scars that do not correspond to fires in the CDF database is represented in the "camfer only" column.

	1999			1996		
Eco-Region	cdf+camfer	cdf only	camfer only	cdf+camfer	cdf only	camfer only
Cascade Ranges	38,298	120,811	2,169	876	2,835	543
Central Western California	103,159	20,483	118,309	88,409	60,585	14,273
East of Sierra Nevada	0	4,055	3,547	0	926	22,842
Great Central Valley	1,243	12,151	35,451	0	37,401	5,755
Modoc Plateau	3,543	32,786	6,106	3,720	29,012	60,693
Mojave Desert	10,217	5,861	17,771	2,225	11,356	75,391
Northwestern California	135,368	75,107	45,534	81,059	28,287	17,722
Sierra Nevada	27,880	79,096	9,069	62,849	89,608	11,952
Sonoran Desert	0	739	5,184	0	2,206	6,025
Southwestern California	32,960	77,109	63,757	18,515	117,204	52,087
Total	**352,667**	**428,198**	**306,897**	**257,653**	**379,420**	**267,283**
Land Cover						
Forest	253,867	149,353	33,538	96,378	92,806	6,811
Grassland	3,178	26,836	112,833	28	57,851	8,089
Open land	0	5,802	5,586	0	5,631	12,570
Riparian	0	55	3,114	0	1,162	0
Scrub	44,402	87,149	86,253	109,908	143,492	217,899
Wetland	0	0	0	0	614	5,977
Woodland	51,220	159,003	65,572	51,339	77,865	15,936
Total	**352,667**	**428,198**	**306,897**	**257,653**	**379,420**	**267,283**
Percent of CDF Mapped Acres	**45%**	**55%**	**39%**	**40%**	**60%**	**42%**

Both the intersection and hit-or-miss methods illustrate that the Sierra Nevada Mountains and the West coast of California (notably North and Central) are the most active geographic regions for wildfire. Detection levels are highest in the Sierras and the Northwest Coast in both 1999 and 1996. Both methods also indicate a decisive lack of mapping accuracy in grassland systems, in contrast to the success achieved in the forest and scrub ecosystems.

There is a sizeable amount of what we assume to be overestimation in the scrub and grassland ecosystems. This area represents mapped burn scars that do not correlate with any fires in the CDF database. Due to the uncertainty inherent in the CDF database, it is impossible to judge whether the unmatched burn scars are false detections, or whether there is an under-reporting of burned area in the CDF database. The intersection analysis shows the regions with a large amount of "false" positives to be Southwestern and central Western California in 1999 and the Mojave desert and Modoc plateau in 1996. These are all heavily scrub and grass dominated regions (Figure 1) that experience high temperatures during the summer.

Figure 4 shows the mapping results of selected fires from 1999 and 1996. These are large fires that were more or less effectively mapped by the CAMFER algorithm. The figure serves to indicate the amount which large fires influence the comparison results. A single fire can represent over 100,000 acres: A significant acreage in context of the totals shown in Table 1. These large fires represent a very significant fraction of the total fire area mapped in any one year. In the 1999 CAMFER map, just *two* fires represent 39% of the annual burn area (the area mapped in the Megram fire, Figure 4(f), as well as the Kirk North and South fires, Figure 4(e)). The fires displayed in Figure 4 also illustrate the trend of many-to-one relationships between the fires in the CDF database and the CAMFER fire maps. This effect can occur in both directions: one CDF fire is mapped by multiple CAMFER burn scars (Megram Fire, Figure 4(f)), or multiple CDF fires are mapped as one CAMFER burn

Table 4. Percent detection by area of intersection compared to CDF total area. Computed using the intersection method. These data indicate less effective detection compared to the more relaxed rules of matching in the hit-or-miss method (see Table 2 percentages, at bottom).

Land Cover	1999	1996
Forest	63%	51%
Grassland	11%	0%
Open land	0%	0%
Riparian	0%	0%
Scrub	34%	43%
Wetland	N/A	0%
Woodland	24%	40%

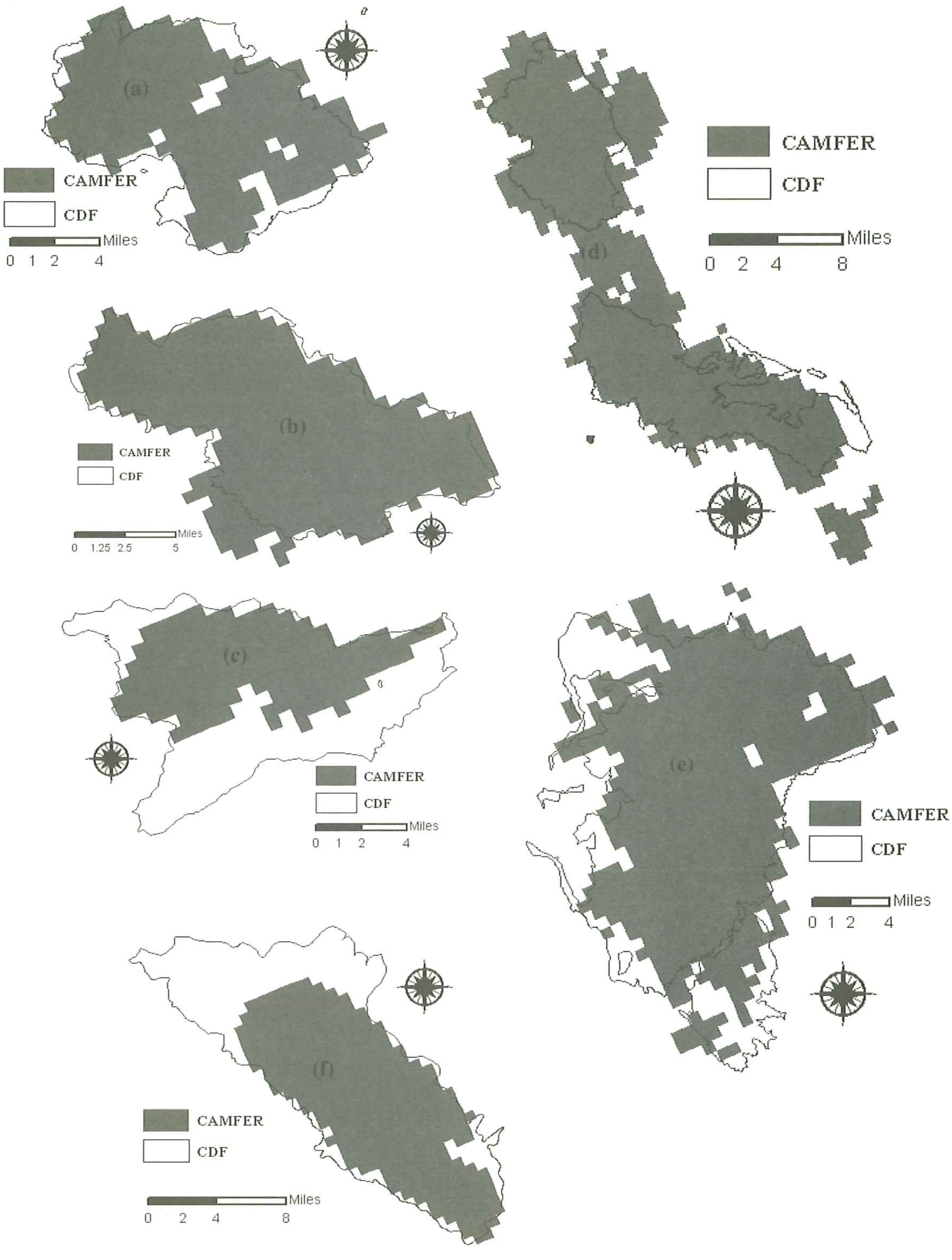

Figure 4. The mapping results of selected fires. The scale differs slightly between these fires (see associated legends). (a). Ackerson fire, Tuolumne County, 59,111 acres; (b). Parks fire, Lake County, 83,057 acres; (c). Gun II fire, Tehama County, 60,389 acres; (d). Kirk fires (North and South), Monterey County, 85,495 acres combined; (e). Megram fire, Humboldt and Trinity Counties, 124,442 acres; (f). Un-named fire, San Luis Obispo County, 106,718 acres.

scar (Kirk fires, Figure 4(e)). The skewed distribution of fire sizes and the many-to-one relationships complicate the description of the data in terms of average fire sizes. Many small fires result in a fairly small average fire size (3973 acres in the 1999 CAMFER burn scar map) that does not reflect the contribution of very large fires (over 50,000 acres, for example) to the overall mapping success.

In general, the CAMFER algorithm is more effective in the mapping of large fires. Despite the inherent uncertainty with averages described above, the data are descriptive when one considers the CDF fires that were mapped. The average size of CDF "detected" fire in 1999, according to the hit-or-miss method, is 10,329 acres while the average undetected fire size is 766 acres. 1996 data displays a similar trend, with an average detected fire size of 14,062 acres and average undetected fire size of 805 acres. This trend is consistent with the results reported by Fraser (2000) and Remmel and Perera (2001) for the Canadian boreal forest. It also illustrates the constraints associated with the AVHRR spatial resolution of one square kilometer, approximately 247 acres. Fires less than 247 acres in size are likely to be excluded from detection, though these fires represent a fairly small component of the CDF fire database (approximately 12,000 acres in both 1999 and 1996).

V. DISCUSSION AND CONCLUSIONS

The data indicate that the success of a remote sensing approach to burn scar mapping is dependent on cover type. That the percent mapping accuracy is so similar over two fairly different fire years reinforces the conclusion that forest lands are more effectively mapped by this algorithm than any other cover types. It is worth noting that in the use of different thresholds and different length intervals for NDVI change only resulted in approximately 10% difference in mapping success between 1999 and 1996 (see Table 4). The relative accuracy of RS based fire mapping in different cover types is only slightly affected by these differences.

These differences may be due in part to the behavior of fire in different ecosystems. Rapid fire spread and short flaming phases in ecosystems such as grassland may confound the ability of the NOAA-14 satellite to pick up hotspots within active fires. The NOAA-14 satellite has only one daytime overpass, restricting the ability to detect fires that burn and go out while the satellite is on the other side of the Earth. To a lesser extent, this may affect fire mapping in scrub, chaparral and shrub dominated ecosystems as well. At the same time, the rapid re-growth of vegetation in grass and shrub dominated systems may restrict the ability to detect changes in NDVI that result from fire. Thus temporal restrictions in both NDVI differencing and hotspot detection may combine to constrain burn area mapping in ecosystems characterized by high rates of combustion and re-vegetation.

Burn area mapping accuracy may be improved, in all regions and cover types, through the use of a wider variety of sensors' data. Higher temporal and spatial resolution of data from sensors other than (or in addition to) AVHRR could increase the number of hotspots detected and used as input to the burn scar mapping algorithms. The successful mapping of burn scars may, in turn, be improved through a more adaptive adjustment of threshold values for NDVI decrease. While it is not possible to increase burn scar discernment in systems that *increase* in NDVI (such as an annual grassland) over the study period (one year in this case), it may be possible to increase accuracy in forest land without adding an excessive amount of false detection. The development of a hybrid approach using combinations of thermal sensor inputs, threshold values, and NDVI differences over various time scales may be appropriate for fire mapping over very large spatial scopes. By determining the appropriate combination of inputs for various ecosystems, mapping accuracy may be improved through algorithm customization to the array of land cover types in the study area.

The fact that the CDF fire dataset is not a perfect ground-truth reference complicates comparisons with other fire map products. Rather than validation of remotely sensed data, comparison to the CDF dataset is, by necessity, a juxtaposition of two approaches to building an annual fire area inventory. While the CDF layer benefits from on-the-ground observation and measurement of burn area, this quality is a double-edged sword. This is due to the fact that multiple agencies contribute to the dataset, each from their respective land base. Some level of omission of burn area is possible through this process. Standardization of the submission, documentation, completeness, and positional accuracy of burn area maps would be a tremendous benefit to the utility of the CDF dataset.

The remotely sensed map of burn area suffers from a different set of constraints: the detection of burn area not from field personnel, but from a satellite in space. Due to the inherent limitations of the sensor, fires of a certain size are automatically excluded from detection. While these fires do not make a significant portion of the total burn area, they are never the less a component of a burn area inventory. Errors of commission are also of concern outside forested areas. When there is uncertainty in the dataset (CDF) used for comparison, it is difficult to judge the extent of this problem. However, the data indicate that this is an issue requiring further inquiry into the field conditions that might be responsible for "false" detections.

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