PEER-REVIEWED ARTICLE

Global Fire Mapping and Fire Danger Estimation Using AVHRR Images

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Abstract

A critical review of AVHRR images for large-scale fire applications is presented. Discussion is divided into fire detection and mapping, on one side, and fire danger estimation, on the other. In both cases, the main lines of research are reported, as well as the problems faced. Finally, some future research guidelines are suggested.

The Role of Fire in Global Studies

Biomass burning is one of the key factors affecting global processes (Figure 1). During the combustion itself, a large amount of trace gasses are released, strongly affecting atmospheric chemistry (Crutzen *et al.*, 1979). Frequently, fire results in a partial or complete destruction of vegetation cover which modifies the radiation balance by increasing the albedo, as well as the hydrological cycle, while raising soil erosion.

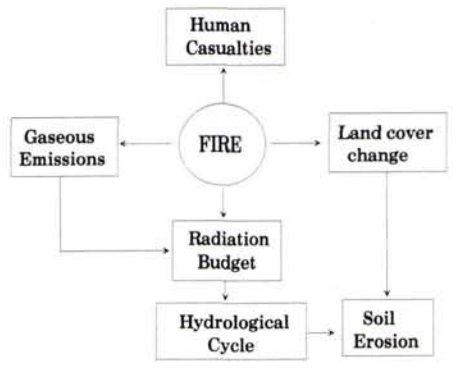

Figure 1. Global implications of biomass burning.

The increased rate of biomass burning in the last decade is estimated to be caused by the increment of tropical deforestation in the Amazon basin and from the augmented rate of burning in cultivated areas in the African savanna. This increase in the amount of released gases to the atmosphere has important effects on atmospheric processes and global climate. The main effects include the following (Kaufman *et al.*, 1992):

- Some of the emitted gases (CO$_2$, CO, CH$_4$, CH$_3$Cl) represent an important contribution to the greenhouse effect that heats the atmosphere. Concentrations of CO as high as 3,700 ppbv (particles per billion volume), which are 50 times higher than during normal atmospheric conditions (Stearns *et al.*, 1986), have been measured over a smoke plume.
- Smoke emissions also include reactive gases, such as NO$_x$ and CH$_4$, which cause elevated levels of ozone and acid rain. Ozone concentrations in intense fire areas have been found to be as much as four times greater than regular levels, reaching 70 to 80 ppbv (Kaufman *et al.*, 1992; Setzer and Pereira, 1991b).
- Biomass burning is also a major source of organic hygroscopic particles which increase the available cloud condensation nuclei. Such increase generates brighter clouds that reflect solar radiation to space, thus reducing the temperature (Robock, 1988).
- Finally, burning is also a source of graphitic carbon which increases absorption of solar radiation by the atmosphere and by clouds and, as a result, implies a heating effect.

On a local scale, biomass burning also has strong effects on the landscape and ecology, especially in semiarid lands. Changes in traditional land-use patterns have recently modified the incidence of fire in these territories. For instance, rural abandonment in the European Mediterranean basin has implied an unusual accumulation of forest fuels which increase fire risk and fire severity. In tropical areas, recurrent use of fire as a soil fertilizer, or as a means of pasture improvement, involves soil and grass degradation in many areas as the fire cycles are shortened (Cahoon *et al.*, 1992). Fires also modify the hydrological cycle, by increasing the runoff as a consequence of less soil protection. Finally, wildland fires also have direct effects on human casualties (Jijia *et al.*, 1989).

Remote Sensing of Forest Fires

Remote sensing systems may be very valuable in different aspects of fire management problems. First, they contribute to pre-fire planning, which is directed to the optimum organization of resources for fire emergencies. This phase involves knowledge of risk conditions, forest value, land quality, weather patterns, fuel conditions, and topographic data. These variables are closely related to fire ignition and rate of spread.

The second phase of fire management is directly associated to the fire itself: detection, suppression, and burned land mapping. Systems are required to provide information on fire active areas. They should operate day and night, despite low visibility caused by smoke or dense timber cover,

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and give some guidelines to distinguish between potentially dangerous fires and those of no concern. Finally, post-fire evaluation makes it possible to reduce the effects of wildland fires. Timely damage assessment should provide critical information for planning the recovery of forest stands (Smith and Woodgate, 1985) and to avoid soil erosion (Isaacson *et al.*, 1982).

Airborne remote sensors have been used since the late sixties for fire spot detection (Hirsch *et al.*, 1971). With the development of the Landsat program during the 70s, several projects were conducted to test the reliability of satellite imagery for forest fire research. These applications, as well as the ones derived from NOAA-AVHRR data, may be classified in the following themes: (1) detection of fire spots, (2) cartography of burned areas, (3) estimation of gas emissions, (4) assessment of fire effects and plant cover evolution after the fire, (5) monitoring forest fuel conditions (vegetation moisture stress), and (6) development of risk models by the integration of image interpretation within a Geographic Information System.

All of these topics complement and improve traditional techniques of fire management (Table 1). In this paper, we will emphasize the global, large-scale approach, which has been mainly based on NOAA-AVHRR images. We have grouped our review in two primary areas: fire detection and mapping, and fire danger estimation. The first one has received more attention by remote sensing specialists, as traditional sources provide generally poor and costly estimations of burned area. Fire danger estimation requires more research, in order to address the complexity of factors affecting fire ignition and fire rate of spread.

Fire Mapping from AVHRR Images

One of the main problems affecting fire management is the lack of appropriate statistics on burned land. Even the countries more severely affected by this problem do not have proper data on fire incidence, as most of the time fires are not mapped and only general statistics are available. The example of Brazil is especially outstanding. The latest statistics available from the Food and Agriculture Organization (FAO) (Calabri and Ciesla, 1992) estimated that 54,280 hectares were burned in that country during 1987. A project based on AVHRR images for the same summer season increased that estimation to 20 million hectares (Setzer and Pereira, 1991a), almost 400 times higher than official statistics! However, it should be remarked that FAO statistics only include the littoral states of Brazil. This results from lack of access to data on the Amazonian basin, which is the most affected area.

Although the Brazilian case can not be considered as the rule, it is a good example of the weaknesses associated with traditional sources of wildland fire data. Logistical inaccessibility of many tropical forest areas make global statistics for those countries quite uncertain, which causes severe difficulties in setting up global fire management strategies. In those areas, the use of satellite information can be considered the most reliable method to generate global statistics on wildland fires.

Countries with more detailed fire reports generally provide more precise statistics. However, the data are not available until several weeks (or even months) following the fire event. As a result, vegetation recovery is not assessed, and a lack of regrowth may constitute a severe soil erosion hazard (Isaacson *et al.*, 1982). Moreover, these field inventories are often very general. Usually, only the scorched perimeter is drawn, but no information about the species affected or severity of damage is provided. Finally, studies on vegetation succession after fire are seldom done.

Fire detection and mapping have been based mainly on middle infrared data. Considering that forest fires temperatures commonly range from 500° to 1,000°K (Robinson, 1991), the most suitable band for fire detection is located between 5.8 and 2.9 μm according to Wien's displacement law. Hot areas in this channel show a strong radiometric contrast with respect to thermal infrared bands, which are better adapted to the average Earth temperatures (300°K).

Fire detection from space is obviously very much dependent on observation frequency. The Earth resources satellites (such as Landsat or SPOT) do not provide enough time coverage for fire detection. On the contrary, meteorological satellites have proven to be very useful for these purposes. NOAA-AVHRR images are well suited for fire detection and mapping because of their adequate coverage cycle (12 hours) and wide spectral range, which also includes the middle infrared (Kidwell, 1991).

The use of AVHRR images for fire detection and fire mapping has been successfully tested in southeast Asia (Malingreau *et al.*, 1985; Malingreau, 1990), Canada (Chung and Le, 1984; Flannigan and Vonder Haar, 1986), the U.S.A. (Matson and Dozier, 1981; Matson *et al.*, 1984), Australia (Hick *et al.*, 1986), Africa (Langaas, 1992; Malingreau *et al.*, 1990), China (Jijia *et al.*, 1989; Chandga *et al.*, 1991), and Brazil (Matson and Holben, 1987; Kaufman *et al.*, 1990a; Setzer and Pereira, 1991b).

In Canada, high accuracy for detecting large-scale forest fires was found in a pilot study conducted in Alberta (Flannigan and Vonder Haar, 1986). Overall, 46 percent of the total number of fires were located with data obtained from AVHRR channel 3. This accuracy raised to 80 percent when only cloud-free fires were considered. Precision reached 95 percent, when refering only to medium or large fires (over 40 hectares). Accuracy for small fires was limited, 10 to 12 percent, although better results were reported if only cloud-free areas were taken into account (up to 87 percent).

In the Brazilian Amazonia several projects have been developed to estimate the total area burned yearly, in order to derive deforestation rates for the whole country. For the summer season of 1987, analysis of AVHRR channel-3 images yielded a total estimation of 350,000 fires, covering as much as 200,000 sq km (Setzer and Pereira, 1991b). These results were obtained from the extrapolation of observed fires in 46 AVHRR images acquired from July to October. Pixels with high temperatures in channel 3 were labeled as fires. This calculation was extended to the whole study period using the following formula:

$$At = \frac{(n \times d)}{t} \times Ap \times f$$

where At is the total area burned, n is the average number of pixels labeled as fire within the summer season (n = number of fire pixels / number of images), d is the length in days of the summer season (80 in this case), t is the average time of fire duration in days (1.5 in this case), Ap is the pixel area (sq km), and f is an adjusted factor to account for the saturation of channel 3 (see below). Successful results of the 1987 project based the extension of this methodology to an operational program. This program has been carried out since then by the Brazilian Institute of Space Research (INPE) (Setzer and Pereira, 1991a).

The study of Setzer and Pereira also estimated the

Table 1. Use of Remote Sensing Techniques Versus Traditional Methods for Fire Management at Local and Regional Scales

	Danger/Risk Estimation	Detection/ Mapping	Smoke Emissions	Effects
Traditional Methods	Weather Stations Fuel maps	Field Sketches	Aerial Samples	Only for managed areas
Remote Sensing	TM-MSS-HRV... + G.I.S. (Risk)	Airborne IR TM-MSS-HRV...	Airborne/ Groundborne	Multitemporal high resolution
Traditional Methods	Weather network Historic records	Statistics from fire reports	Not available	Not available
Remote Sensing	AVHRR NDVI and Thermal	AVHRR Ch. 3 Geostationary	AVHRR visible MAPS/TOMS	AVHRR multi-temporal series

amount of gases released to the atmosphere from the 1987 Brazilian Amazonian fires. Based on a simple method, total amounts of 1,700 Tg of CO_2, 520 Tg of C, and 94 Tg of CO were calculated (Setzer and Pereira, 1991b). More detailed projects to measure gas emissions from tropical forest have been carried out using satellite, airborne, and field sensors (Kaufman *et al.*, 1990a and 1992).

Most of the work related to gas release is based on the determination of optical thickness, particle size, and single scattering albedo using short-wave bands. Kaufman *et al.* (1990b) developed a self-consistent algorithm for simultaneous determination of smoke characteristics. This method is based on satellite images of the surface (land and water) in the visible and near infrared bands. The algorithm derives the aerosol characteristics from the difference in upward radiances between two images of the same area, one acquired on a clear day, and one during hazy conditions. This method was applied to the estimation of smoke concentrations over the Chesapeake Bay coming from Canadian fires. A close relation was found between the aerosol estimation from AVHRR data and ground measurements (Kaufman *et al.*, 1990b). A more qualitative approach was adopted by other authors to estimate the area affected by smoke plumes in large-scale forest fires (Chung and Le, 1984; Jijia *et al.*, 1989). There are also some examples of using space photographs for smoke monitoring. From the comparison of Skylab (1973) and Space Shuttle photographs (1986), a tenfold increase in smoke pall surfaces was estimated (Herfert and Lulla, 1990).

In addition to the use of AVHRR imagery, other sensors have proven to be efficient for fire detection and mapping. These include geostationary data (Prins and Menzel, 1992) and DMSP night images (Cahoon *et al.*, 1992). Smoke emissions have also been monitored from the MAPS (Measurement of Air Pollution from Satellites) experiment on board the Space Shuttle (Watson *et al.*, 1990).

Problems for Operational Fire Mapping

The main problem of AVHRR data for these applications is the low thermal sensitivity of channel 3, which is saturated at 320°K. As a result, fire spots can be easily confused with agriculture burns or even bare soils, which frequently reach these temperatures during the summer at the afternoon pass (Belward, 1991). Discrimination from agricultural fires could be partially achieved by choosing evening or night images, because this type of burning tends to be done during daylight periods (Malingreau, 1990). The confusion with adjacent areas is not a severe problem in tropical forests, because the vegetation surrounding the fire is much cooler than saturation temperatures caused by evapotranspiration. In the case of semiarid lands, fire active areas and bare soils may be discriminated on night images, due to the fact that bare soils are cooler than fires at that time (Langaas, 1992). Monitoring the temporal dynamism of the target surfaces also provides good classification of fire pixels (Lee and Tang, 1990). In any case, sensors with higher thermal sensitivity are desirable. In the Brazilian Amazonia, airborne experimental fire detection scanners with saturation levels up to 900°K have been successfully tested (Riggan *et al.*, 1993). The future Moderate Resolution Imaging Spectroradiometer (MODIS) will include a middle infrared channel that saturates at 500°K, which will notably increase the potential of satellite fire detection systems.

On the other hand, low thermal sensitivity of AVHRR creates problems of overestimation of the burned area. It should be noted that a pixel may be saturated even if only a small proportion is actually occupied by fire. In fact, fires with a temperature above 500°K, even if they occupy less than 0.1 percent of the pixel size, will most likely reach pixel saturation temperatures (Kaufman *et al.*, 1990a). For this reason, a consistent tendency of overestimation has been found when AVHRR channel-3 fire mapping estimations are compared with higher resolution data, such as Landsat MSS or TM. According to several experiences in the Amazon basin, this overestimation is on the order of 43 percent, or 1.5 times the areal extent observed with Landsat TM (Setzer and Pereira, 1991a).

Cross analysis of channels 3 and 4 might partially solve this problem as the difference in radiances between both channels will increase when a greater percentage of a pixel is occupied by an active fire. This proportion, as well as the actual temperatures of the fire, may be calculated following a method proposed by Dozier (1981) and Matson and Dozier (1981), which uses the radiance contrast between channels 3 and 4 of AVHRR: i.e.,

$$L_3 = pL_3(T_i) + (1-p)L_3(T_b)$$

$$L_4 = pL_4(T_i) + (1-p)L_4(T_b)$$

where $L_i(T_i)$ is the radiance in band i as a result of the fire temperature (T_i), T_b is the background temperature (which can be estimated from areas nearby the fire), and p is the proportion of the pixel size occupied by the fire. In spite of its interest, it should be noted that Dozier's algorithm only works properly when pixels are not saturated and does not take into account the attenuation caused by water vapor in both bands. Pixel saturation may be solved by using a wider IFOV sensor, less likely to be saturated by a small fire. This was the basis of using GOES-VAS thermal channel (7- by 7-km pixel size) and middle infrared for detecting fires in the Amazonian basin (Prins and Menzel, 1992). Emphasizing these radiance differences between channels 3 and 4 by tree-decision rules and contextual methods have also been proposed for an automatic discrimination of fire active areas (Lee and Tag, 1990; Illera *et al.*, 1993).

Another source of problems for using AVHRR channel 3 in fire detection is cloud cover. Although the middle infrared channel makes it possible to discriminate fires when clouds are thin (Figure 2), cloud contamination is still an important source of errors. Small fires are frequently obscured by thick clouds which make their discrimination especially problematic (Flannigan and Vonder Haar, 1986; Setzer and Pereira, 1991a).

Fire Danger Estimation

Forest fire literature usually discerns between the concepts of fire risk and fire danger. The former is related to causality, and is commonly divided between human induced and lightening. The latter is more associated with weather conditions which account for vegetation stress status and, consequently, are closely connected to flammability. Most of the current fire danger indices rely on temperature, air humidity, and wind for estimating vegetative status (Van Wagner, 1987). Direct measures of vegetation and duff moisture are much more complex and require costly spatial sampling. Consequently, they cannot be used in global fire danger estimations.

The main problem associated with meteorological measures is the generally sparse geographical distribution of observation points. In spite of the increasing use of automatic weather stations, climate data are frequently available only for areas that are distant from the forest land. Interpolation is performed on a very rough basis, especially in complex terrain zones; this may cause fire danger values to vary significantly from the original points of measure.

Remote Sensing of Vegetation Stress

Several studies have shown strong correlations between AVHRR spectral vegetation indexes and critical physiological variables. Primary examples are green biomass, Leaf Area Index, evapotranspiration, primary productivity, and Active Photosynthetically Absorbed Radiation by the plant (APAR) (Sellers, 1989). Most of these studies found significant statistical correlations between NDVI and vegetation trends (seasonality: Cihlar *et al.*, 1991), but the relationships are much weaker for short periods, i.e., one or two weeks (Deblonde and Cihlar, 1993).

Fire danger estimation demands frequent monitoring of vegetation stress. Vegetation moisture is a particularly difficult parameter to estimate as it accounts for little spectral variation with respect to other environmental factors (Cohen, 1991). However, spectral characterization of vegetation stress is possible if temporal profiles are derived, and the contrast between living and dead components is emphasized.

The most common vegetation stress estimation has been the analysis of NDVI multitemporal series. As mentioned previously, NDVI increase is related to LAI and APAR. Therefore, this vegetation index provides a good indication of vegetation healthiness. On the other hand, decrements of NDVI are related to reduction of plant vigor and greenness, which are also connected with vegetation moisture content. Multitemporal accumulated NDVI composites have been successfully correlated to accumulated evapotranspiration (Kerr *et al.*, 1989; Deblonde and Cihlar, 1993), rainfall amount (Kerr *et al.*, 1989), and crop moisture indices (Walsh, 1987) for semiarid environments. Strong correlations between NDVI and soil temperature have also been measured (Dabrowska, 1991).

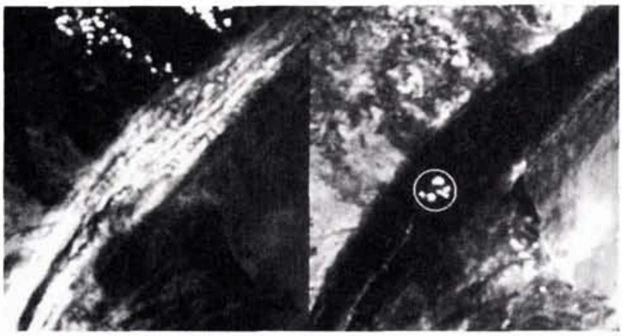

Figure 2. AVHRR images of a wildland fire in the Mediterranean coast of Spain. (Left) Clouds in the visible channel screen the active fire. (Right) Channel-3 image clearly displays the fire focus because the fire has a strong radiometric contrast with clouds in this spectral channel.

An alternative to the use of NDVI series for vegetation moisture estimation is to follow the thermal dynamism of the vegetation cover. Although not directly related to fire danger, several studies on crop moisture might be quite useful for fire danger estimation, as they deal with vegetation spectral behavior under drought conditions.

Vegetation moisture stress can be measured as the ratio of actual and potential evapotranspiration (ET/PET). ET has proven to be linearly related to net radiation and to the difference between air and surface temperature. The consistency of this relationship is increased when applied to accumulated periods of five or ten days (Seguin et al., 1991): i.e.,

$$\Sigma \mathrm{ET} = \Sigma R_n + n\, a - b\, \Sigma\, (T_s - T_a)$$

where ET is the actual evapotranspiration, R is net radiation, T_s and T_a are surface and air temperatures, respectively, and a and b are adjustment constants. Over long term periods and at regional scales, correlation coefficients of $r=0.99$ between accumulated values of $(T_s - T_a)$ and Σ ET $- R_n$ have been measured (Seguin *et al.*, 1991). This relationship might successfully be applied to fuel moisture estimation, complementing the analysis of NDVI time series.

Use of AVHRR Data in Fire Danger Estimation

Several projects developed so far have addressed the operational application of NDVI multitemporal profiles for fire danger estimation. To avoid atmospheric disturbances, most of these studies have used weekly or biweekly maximum value composites. The results have been very precise for areas of homogeneous and herbaceous vegetation. In Nebraska, NDVI was used to estimate percent of green cover and biomass. Correlations of $r=0.75$ with biomass percent and $r=0.82$ with green cover were obtained using several grassland areas as test fields (Sadowski and Westover, 1986). A similar study in four states (North and South Dakota, Nebraska and Kansas) obtained very good correlations between weekly NDVI composites and percent of green cover (r^2 ranged from 0.86 to 0.6). These results were used as an input of a fire danger index at county level (Eidenshink *et al.*, 1989).

Significant relationships between NDVI and fuel moisture have also been found in herbaceous lands of Australia (Paltridge and Barber, 1988). In this case, a variation of NDVI was suggested to better identify the maximum green component: i.e.,

$$V = (\mathrm{NIR} - \mathrm{R} * 1.2) / (\mathrm{NIR} + \mathrm{R})$$

where NIR and R are the near infrared reflectance and red reflectance, respectively. From the V value, fuel moisture content was estimated according to the following formula:

$$\mathrm{FMC} = 250\ V(\mathrm{t}) / V(\mathrm{nov})$$

where FMC is the fuel moisture content, V(t) is the vegetation index at any specific time, and V(nov) is the same measure on a November image, the time of maximum vegetation vigor in Australia.

Temporal profiles of FMC estimated by AVHRR images and ground measured data followed a similar trend, with close relationship between NDVI estimation and fuel moisture measures on the ground (Paltridge and Barber, 1988).

These results from grasslands need to be extended to shrub and forest lands, where fire has more severe effects. With this objective, an experimental study has been conducted in four States of the Great Plains (Eidenshink *et al.*, 1990). This study assumed that the relation between NDVI evolution and vegetation moisture would be very different for grasslands and shrub-forest lands. For the former, dryness and wetness are much more uniform. As a result, NDVI calculated from grasslands varies along with LAI and chlorophyll production. On the contrary, in shrubs and forest lands new growths and higher moisture contents may be spectrally veiled by the more cured components of the plant. Consequently, to monitor actual vegetation conditions, it has been suggested that the relative instead of the absolute variations of NDVI be analyzed. The authors proposed three indices:

- $\mathrm{GRN_{rel}} = 100\ (\mathrm{ND_o} - \mathrm{ND_{min}})/(\mathrm{ND_{max}} - \mathrm{ND_{min}})$
  where $\mathrm{GRN_{rel}}$ is relative percent green, $\mathrm{ND_o}$ is the observed NDVI for an specific pixel, and $\mathrm{ND_{min}}$ and $\mathrm{ND_{max}}$ are the maximum and minimum NDVI of that pixel for the whole study period.
- $\mathrm{GRN_{abs}} = 100\ (\mathrm{ND_o} - \mathrm{NR_{min}})\ \mathrm{NR_{max}}$
  where $\mathrm{GRN_{abs}}$ is the absolute percent green, $\mathrm{NR_{min}}$ corresponds to the minimum NDVI for fully cured grass (0.05), and $\mathrm{NR_{max}}$ is the maximum NDVI observed in the historical record of multitemporal composites of United States (0.66).
- $\mathrm{SM} = 250\ (\mathrm{GRN_{rel}} + \mathrm{GRN_{ab}})/2$
  where SM is site moisture, $\mathrm{GRN_{rel}}$ and $\mathrm{GRN_{ab}}$, are the fractional relative and absolute percent green for any specific pixel on a given date.

Although no quantitative evaluation with ground data was performed in this study, seasonal trends of these indices were clearly associated so they could provide updated information concerning greenness evolution for forest stands. The introduction of these greenness calculations in forest fire danger indices has already been addressed (Burgan and Hartford, 1993).

Finally, another method to estimate fire danger is based on the accumulative decrements of NDVI values in each pixel over a dry season. A project developed on the Mediterranean coast of Spain tested this method. Daily images were used instead of maximum composites. Cloud cover and view-angle effects were minimized by selecting only the most suitable images for the study area. A set of seven images on the summer of 1987 was used to point out those areas with higher NDVI decrements over the study period. One of those areas happened to be affected by a large forest fire at the end of that period (López *et al.*, 1991).

Fuel Maps

Form, size, arrangement, and continuity of vegetation are critical variables for fire behavior prediction. Usually, the vast diversity of vegetation associations require that they be organized into generalized categories referred to as fuel types. It is then possible to define the fuel types as complexes of sufficient homogeneity and size to maintain a coherent fire behavior over time (Van Wagner *et al.*, 1992).

Although fuel types are less time dependent than fuel moisture, updated cartography is required for fuel management and fire behavior prediction systems. Remote sensing is an ideal tool for mapping fuel types, but it faces several problems. Fuel types are defined by both the canopy and by the understorey vegetation. Strictly speaking, this discrimination would be very complex in dense stands as remote sensors only obtain information from the canopy. However, most of these fuel types such as boreal spruce or conifer plantation are considered standard vegetation associations, which might be related to canopy spectral characteristics.

Several studies have successfully mapped fuel types using Landsat images and auxiliary variables, such as topography or soils types (Burgan and Shasby, 1984). These studies are useful for local-scale management, but are not suitable for global fuel management where low resolution sensors are required. This global approach has been adopted by several projects which compiled fuel maps from AVHRR data. Areas as large as the ten western states of the U.S.A. were used to test the suitability of these images (Werth *et al.*, 1985). Results have shown that general discrimination was accurate enough, but some fuel models of the National Fire Danger Risk System (NFDRS) had to be digitized from auxiliary sources.

A more detailed study conducted in Oregon (Miller *et al.*, 1986) showed 92 percent accuracy from an unsupervised classification of four AVHRR images. Ancillary information was also used in this project in order to label the 45 clusters generated, as well as to group them into 11 fuel types of the NFDRS. Elevation, roads, and visual interpretation were applied to discriminate categories with high spectral overlap.

Most recent developments of GIS techniques will allow for easy generation of fuel maps from AVHRR images and auxiliary information, as more global data will be available for labeling and discrimination of the most problematic categories. The experiences gained from the land-cover maps of the conterminous U.S.A. are quite promising for this application (Brown *et al.*, 1993).

Conclusions: Scenarios of Future Research

As reviewed in this paper, the combined use of AVHRR channels makes it possible to acquire valuable information concerning (1) the geographical origin of the fires, (2) their spatial and temporal development, (3) their effects, and (4) those parameters related to fire ignition and behavior.

Fire Mapping

In spite of the efforts developed so far, several possibilities in using AVHRR data for fire detection and mapping are still subject to future improvements. First, there is no quantitative application of a daily series of AVHRR data to monitor fire growth. This product could be quite interesting as an input to improve fire behavior programs such as BEHAVE (Burgan and Rothermel, 1984), or as a way of testing their performance. Fire growth studies might take advantage of the time coverage of AVHRR channel-3 data to monitor daily (or even twice a day, using night images) fire evolution in the case of

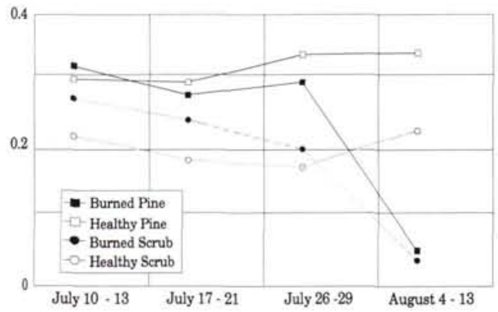

Figure 3. NDVI temporal profile for healthy and burned areas of pine and scrub vegetation. Data were obtained from weekly maximum value composites of AVHRR images on the Mediterranean coast of Spain. The reduction of NDVI values after the fire is evident.

large events. A preliminary study of a 20,000-hectare forest fire on the Mediterranean coast of Spain has shown a very promising future for this approach (Chuvieco *et al.*, 1993).

On the other hand, most of the fire mapping research developed so far is based exclusively on channel-3 data. Multitemporal analysis of NDVI values has rarely been used for this purpose (Matson and Holben, 1987). Working with multitemporal series of NDVI values will solve some of the problems previously reported, such as those derived from the thermal sensitivity of AVHRR. Cloud-free and near-nadir images from before and after the fire might be used for quantitative evaluation of burned land because the NDVI value is severely reduced after a fire (Figure 3). In using NDVI for burned land mapping, maximum value composites have been employed (Kasische *et al.*, 1993). However, the effect of misregistration errors and cloud contamination may make difficult an accurate evaluation for small fires (Martín and Chuvieco, 1993).

Finally, future improvements in sensor design might greatly affect fire mapping from space. The new generation of AVHRR sensors will produce better radiometric contrast, with higher saturation levels, although this channel will not be operated at daytime. On the other hand, the MODIS instrument will notably augment the spectral information provided by AVHRR, with two new channels at 2.1 and 1.65 μm and higher thermal sensitivity.

Fire Danger Estimation

In spite of the complexity of using AVHRR data for fire danger estimation in forest stands, the experiences with grasslands appear quite favorable for inputing remote sensing data to fire danger indices. However, several problems should be examined in order to make operational use of this technology. Among them, we highlight the following:

- Fire danger requires a short-term estimation. Maximum Value Composites techniques remove most of the atmospheric and view-angle disturbances of daily NDVI values, but they do not provide enough time coverage for fire danger estimation. Methods of radiometric and atmospheric correction of daily images should be improved, in order to have more frequent information on vegetation state.
- Thermal channels of AVHRR should be considered in fuel moisture estimation. As they are clearly related to vegetation's actual and potential evapotranspiration, the accumulated difference of air and satellite derived temperatures might greatly improve current methods based on NDVI series, especially in dense forest stands.
- A more quantitative assessment of NDVI relations with fuel moisture and fire danger indices should be performed.

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