Chapter 3

Use of Remote Sensing in Wildfire Management

Brigitte Leblon, Laura Bourgeau-Chavez and Jesús San-Miguel-Ayanz

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/45829

1. Introduction

Wildfire is the one of the prominent disturbance factor in most vegetation zones throughout the world, like forests and grasslands. Wildfires present a challenge for ecosystem management, because they have the potential to be at once beneficial and harmful. On the one hand, wildfires are a natural part of several ecosystems for maintaining their health and diversity in numerous ways, such as regulating plant succession and fuel accumulations, controlling age, structure and species composition of vegetation, affecting insect and disease populations, influencing nutrient cycles and energy flows, regulating biotic productivity, diversity and stability and determining habitats for wildlife.

On the other hand, wildfires can also become a threat to property, human life and economy, particularly in ecosystems where fires are an uncommon or even unnatural process. Despite the prominence of fire events, current estimates of the extent and impact of vegetation fires globally are still a challenge. Several hundred million hectares of forest and other vegetation types are estimated to burn annually throughout the world, consuming several billion tons of dry matter and releasing emission compounds that affect the composition and functioning of the global atmosphere and human health. According to the FAO (FAO 2012), wildfires are important climate forcing factors as they release aerosol between 25-35% of the total CO_2 net emissions to the atmosphere. Over the last decade in Canada, wildfires have consumed an average of 1.9 million ha/year and induced fire suppression costs ranging from about $500 million to $1 billion a year (Canadian Forest Service, 2012). In Europe, wildfires burn more than half a million ha of forested areas every year. Over 95% of the burnt areas are located in the Mediterranean region, in which critical fire events have taken place in recent years (http://effis.jrc.it).

Because of the threat that fires represent, operational systems have been developed for use in fire management that includes fire danger prediction, fire detection and fire control. Given expected increases in fires across the world due to climate changes, better prediction of fire danger and fire detection will have significant benefits both from the economical and the human safety points of views across the world. There is also the need to accurate assessment of burnt areas because they are related to greenhouse gas emissions into the atmosphere that need to be accounted for following Kyoto's protocol requirements as well as for managing post-fire environmental impacts, such as regeneration and erosion. Space-borne remotely sensed imagery can play an important role in these systems. Indeed, satellite imagery offers the advantages of extensive regional coverage, zero disturbances of the area to be viewed, as well as a method for acquiring data in less accessible areas on a regular and cost effective basis. In the first part of this chapter, we will present the use of remote sensing in pre-fire conditions management. The second part of the section will deal with the use of remote sensing for detecting fires and burn scar mapping.

2. Pre-fire conditions management

Ignition and spread of wildfires depends on fuel moisture and weather conditions as well as on fuel types and topography. These parameters are as inputs into fire danger predicting systems that have been developed for fire management, among others for fire suppression. These systems are among others the *National Fire Danger Rating System* (*NFDRS*) in USA (US Forest Service, 2012) and the *Canadian Forest Fire Danger Rating System* (*CFFDRS*) in Canada (Canadian Forest Service, 1992). The *CFFDRS* is also used in Alaska and in some other parts of the world, including Europe and Asia. Both systems are based primarily on weather parameters that are point source data which are often acquired in a sparse network of weather stations. The availability of satellite images coupled with the development of geostatistics and spatial analyses using geographic information technology allows moving fire danger rating from point-based estimates from weather stations to spatially-explicit estimates. Indeed, satellite images have the advantages of larger sampling areas, lack of destruction of the studied resource, gathering data on less accessible areas and are measuring, in essence, the integrated response of vegetation (including fuel) to environmental influences (including drought).

Several pre-fire conditions can be monitored using remote sensing. The first one is related to the fuel type, which can be mapped, like classical vegetation mapping, from high spatial resolution optical or radar images (e.g., Chuvieco and Martin, 1994; Burgan et al., 1998; Chuvieco et al., 1999a). These maps can then be linked, within a wildfire threat analysis system, to other pre-fire conditions variables, such as topography, proximity to roads and to urban areas, etc... (Burgan et al., 1998; Chuvieco et al., 1999a; Chuvieco et al. 2010). Another pre-fire condition, which can be estimated by remote sensing, is the fuel moisture condition. We will focus here on live fuel moisture conditions, which are in current fire prediction systems, either directly measured (Pinol et al., 1998) or broadly estimated (Canadian Forest Service, 1992). Dead fuel moisture conditions will also be considered, although they can be more easily computed from weather data and fuel characteristics, because dead fuel moisture is in balance with that of the surrounding atmosphere (Burgan et al., 1998; Pinol et al., 1998; Chuvieco et al., 1999b). In most of the remote sensing studies on live fuel moisture estimation, live fuel moisture conditions have been quantified as an absolute measurement of plant water content, through the Fuel Moisture Content (FMC) or the Equivalent Water

Thickness (EWT). FMC is defined as the ratio between the quantity of water (fresh weight–dry weight) and either the fresh weight or the dry weight (see the review of Ceccato et al., 2001). EWT is the leaf water content per unit leaf area which is defined as the ratio between the quantity of water and the leaf area (see the review of Ceccato et al., 2001). Live fuel moisture conditions have been also quantified indirectly, through the degree of water stress which is expressed in terms of evapotranspiration rates (Vidal et al., 1994). In the present study, the term "optical" is used to describe wavelengths between 400 and 2500 nm, in contrast to the thermal infrared bands, which range from 3000 to 15000 nm. Both types of wavelengths are recorded by optical sensors. The present study will primarily focus on satellite data, although the theory may also be applied to airborne sensors, which are currently used during fire suppression activities rather than as fire danger prediction tools.

2.1. Optical remote sensing

The first remote sensing studies on fuel moisture conditions monitoring used optical data, mainly NOAA-AVHRR NDVI images (e.g., Paltridge and Barber, 1988; Burgan et al., 1998; Chuvieco et al., 1999b; Hardy and Burgan, 1999). This supposes that timing and extent of drought can be assessed from vegetation greenness, as retrieved from satellite data. NDVI data were also correlated to simulated forest evapotranspiration (e.g., Deblonde and Cihlar, 1993), to FWI codes and indices (Dominguez et al., 1994; Camia et al., 1999; Leblon et al., 2001; Oldford et al., 2006; Leblon et al., 2007), to fuel moisture content of grasslands (Yebra et al., 2008), and to fire occurrences (e.g., Lopez et al., 1991; Illera et al., 1996; Burgan et al., 1998). NDVI-based operational systems have been proposed to assess fire potentials (Figure 1) (Burgan et al., 1998) and crop droughts or fire dangers (Kogan, 2001).

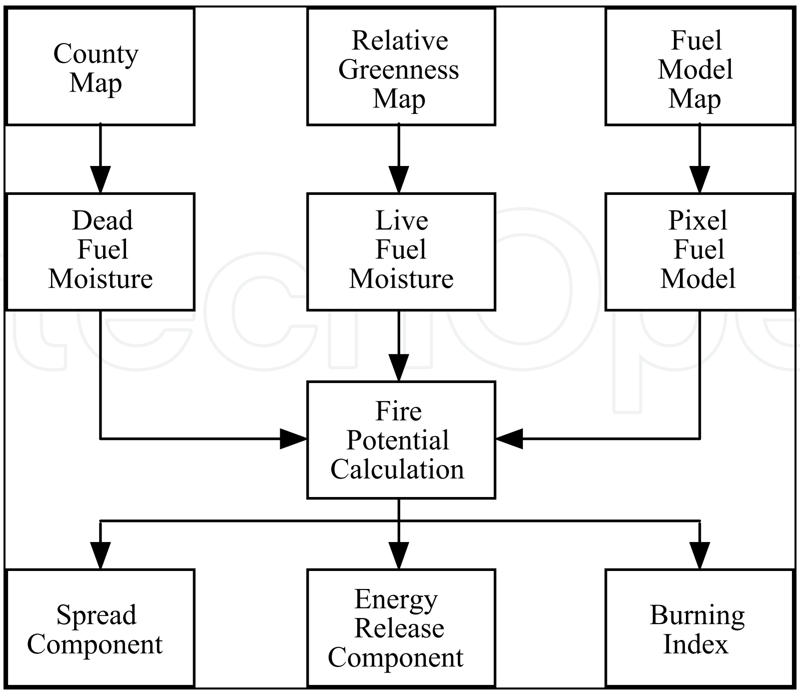


Figure 1. An operational system to compute fire potential maps from NOAA-AVHRR NDVI images (adapted from Burgan et al., 1998)

These studies listed several problems related to the use of NDVI images in fuel moisture mapping, namely the saturation of relationships (Paltridge and Barber, 1988), the influence of site wetness on relationships (Deblonde and Cihlar, 1993) and the difficulty of using NDVI over forests, due to the spectral mixture of the overstory with the understory, both being different in nature and in moisture content (e.g., Hardy and Burgan, 1999; Leblon et al., 2001). In fact, NDVI and associated vegetation indices are only indirectly related to fuel moisture conditions, because it rather measures the greenness and the chlorophyllous activity of the vegetation (Ceccato et al., 2001; Leblon, 2005). In a study on pre-fire conditions using NOAA-AVHRR over Northwest Territories boreal forests, Oldford et al. (2003) showed that high FWI areas correspond to high surface temperature areas on the surface temperature NOAA-AVHRR image, indicating water stress, but to high NDVI areas over the NOAA-AVHRR NDVI image, indicating no drought conditions (Figure 2).

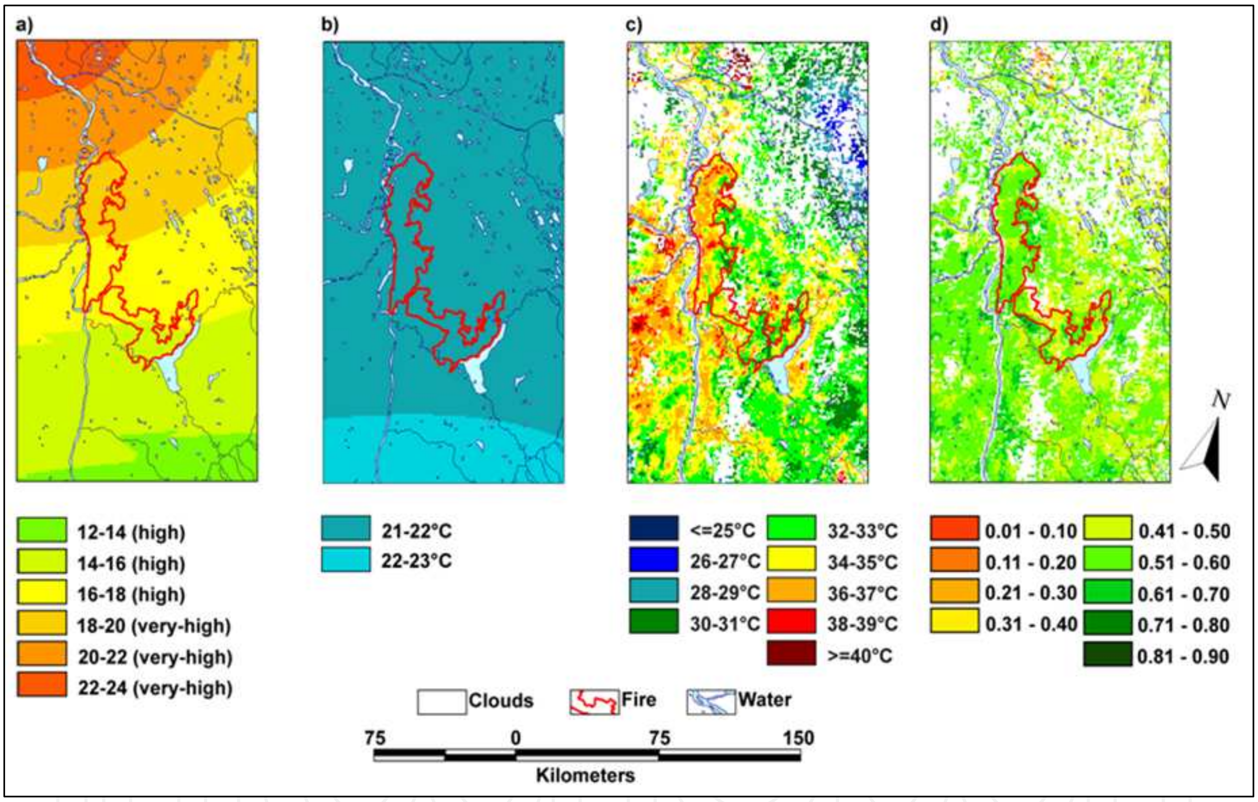


Figure 2. Map of (a) interpolated FWI, (b) interpolated T_a, and corresponding (c) T_s NOAA-AVHRR image and (d) NDVI NOAA-AVHRR image for the area, where the fire "*vq0332*" starts. The image was acquired 3 days before fire ignition (after Oldford et al., 2003)

Greenness and the chlorophyll activity of the vegetation explained the positive correlations between ΣNDVI and FWI codes and indices found by Leblon et al. (2001, 2007) over Canadian northern boreal forests, since both types of variables increase in parallel throughout the fire season, but for two different reasons: FWI codes and indices, because of drought, and ΣNDVI because of vegetation growth. In addition, reduction in NDVI could be induced by factors other than drought, like disease or senescence (Leblon, 2005) and shadowing or penumbra (Chuvieco et al., 1999b). For all these reasons, a better use of NDVI images over forests will be to map timing of deciduous leaf flushing, which is critical in fire management, because of its relationship to fire occurrence in mixed-deciduous forests.

Fuel moisture is theoretically better related to another optical band, the shortwave infrared (1300-2500 nm) (e.g., Pierce et al., 1990; Pinol et al., 1998; Chuvieco et al., 1999b, Ceccato et al., 2001, Yebra et al., 2008). Relationships were significant only when the water stress was already well developed (Pierce et al., 1990; Pinol et al., 1998). Reflectance variations associated with water changes were smaller than those associated with leaf structure (Pierce et al., 1990; Ceccato et al., 2001). In addition, shortwave bands are highly disturbed by atmospheric effects. Fuel moisture is also probably estimated better using hyperspectral data. Indeed, hyperspectral data allow derivative analysis which is useful to remove, on reflectance, the effect of leaf structure, of background and of atmosphere as well as to resolve overlapping spectra to better separate components of the global spectrum (see the review of Leblon, 2005). Hyperspectral data were related to plant water content through empirical relationships (e.g., Pinol et al., 1998) or analytical models (e.g., Ustin et al., 1998; Ceccato et al., 2001). Multispectral data of the MODIS sensor were used into analytical model to retrieve fuel moisture content of shrublands (Yebra and Chuvieco, 2009).

However, from the operational point of view, both hyperspectral data are, up to now, only provided by airborne sensors and shortwave infrared data are acquired by only a few numbers of spaceborne sensors, among others LANDSAT-TM, SPOT-VEGETATION, NOAA-16 and MODIS. While the oldest ones like LANDSAT-TM have a long revisit period, the newest ones, like SPOT-VEGETATION and the new series of the AVHRR sensor, on board NOAA-16, or MODIS, have the advantage to allow daily image acquisition. This temporal scale may be longer on cloudy periods. The performance of these new sensors is still under evaluation. By contrast, for many years, thermal infrared data are provided more often and mostly at the same time as the optical visible and near-infrared ones, by several existing spaceborne sensors, e.g., NOAA-AVHRR, LANDSAT-TM, ATSR-2, RESURS-01, METEOSAT, GOES or MODIS.

2.2. Thermal infrared remote sensing

Surface temperatures (T_s) were better correlated than NDVI to FWI codes and indices (Dominguez et al., 1994; Camia et al., 1999; Aguado et al., 2003; Oldford et al., 2003; Oldford et al., 2006, Leblon et al., 2007), to foliar moisture content (Chuvieco et al., 1999b) and to shrub water potentials (Gouyet et al., 1991). They were also useful to detect water-stressed coniferous stands, when extreme differences in canopy water content occurred (Pierce et al., 1990). In fact, the difference between surface and air temperatures is a better spectral index to monitor plant water status than the surface temperature solely, the last being too sensitive to weather conditions (Camia et al., 1999; Duchemin et al., 1999). In addition, according to the energy budget equation, plants respond to water stress by stomata closure, thereby decreasing latent heat transfer from leaf surface to the air and causing an increase in leaf surface temperature (Pierce et al., 1990). Solving the energy budget equation, in which the sensible heat flux (H) is inferred from the difference between surface and air temperatures

(T_s-T_a), as a function of the latent heat flux (LE) leads to an analytical relationship between actual evapotranspiration rate (AET) and T_s-T_a. Cumulative T_s-T_a data were well related to monthly fire start numbers throughout the fire season over Mediterranean forests (Prosper-Laget et al., 1995). For the same ecosystem, Vidal et al. (1994) used the energy budget equation to compute the ratio between actual and potential evapotranspirations (AET/PET) from daily NOAA-AVHRR surface temperatures and synoptic air temperatures. The ratio was related to fire occurrences (Vidal et al., 1994) and to two shrub flammability variables (Desbois and Vidal, 1996). The ratio was used to operationally monitor fire danger over Mediterranean forests in 1994 (Desbois and Vidal, 1995) and was correlated to FWI codes and indices over Canadian northern boreal forests (Strickland et al., 2001).

However, these studies also showed that estimating AET from T_s-T_a using the energy budget equation is more problematic over forest canopies than over crop canopies (Leblon, 2005). First, canopy height makes forests different from a thin leaf surface, as supposed by the energy budget equation, because of an additional level of radiation absorption and convective heat exchange between the ground and the superior stratum. Second, the measured surface radiative surface temperature is different from the aerodynamic surface temperature (T_{rad}) required by the equation, because of an additional excess resistance (known as the kB^{-1} factor) to heat transfer from leaves, which increases with the canopy height. Third, the aerodynamic resistance (r_a) is lower than the canopy resistance (r_c) and T_s-T_a is thus less sensitive to moisture fluctuations. This lower sensitivity is compensated by the sensitivity of satellite signals to ground vegetation patches which are an important fire danger parameter. Also, the clumped nature of canopy elements in tree crowns reduces wind speed near leaves and allows sunlit leaves to have temperatures elevated well above T_a. Wind can affect temporal fluctuations of T_s-T_a, but these fluctuations on the 1 km pixel basis of NOAA-AVHRR may be very small, because eddies near the surface are on a scale of about 10 m and because of the spatial integration over the pixel.

The energy budget equation requires an estimate for T_a. If synoptic T_a measurements are used, they should be corrected for shelter and tree height effects (Prosper-Laget et al., 1995). They can also be estimated as the radiative surface temperature of nearby well-watered canopies (Duchemin et al., 1999), since for not well-watered canopies, a systematical bias has been observed because the difference between surface and air temperatures is an indicator of water stress. T_a was also estimated as the radiative surface temperature corresponding to the extrapolation of the NDVI/T_s relationship to an NDVI of an infinitely thick vegetation canopy (e.g., Goward et al., 1994). However, such an estimate requires first that the range of variation in NDVI and T_s is enough to accurately define the slope (Pierce et al., 1990). Second, the images should not be contaminated by clouds, snow or standing water, because the slope can then be positive (e.g., Goward et al., 1994). Third, the canopy should be well-watered because the NDVI/T_s slope can changed as a function of the moisture of the canopy. Indeed, the slope was related to several moisture-related variables which are listed in Section 4.

The energy budget equation also requires the knowledge of the aerodynamic and canopy resistances which are difficult to estimate (Vidal et al., 1994; Vidal and Devaux-Ros, 1995;

Strickland et al., 2001) and whose estimates are valid only for small areas. Thereby, other analytical models for computing AET from T_s have been proposed. The first one is the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998). It computes LE as a residual quantity of the energy budget equation, but H is derived from the vertical difference in air temperature (δT_a) between the surface roughness length to heat transport (z_{oh}) and the reference height (z_h), δT_a being directly inferred from T_s. SEBAL has been validated on both short and tall vegetation (Bastiaanssen et al., 1998).

The second one does not compute LE as a residual of the energy budget equation. It uses the Penman-Monteith approach, in which the vapour pressure deficit of the air (VPD) is estimated from the saturation vapour pressure at the mean daily surface temperature (VP^*_{Ts}) (Granger, 1997). Indeed, according to the feedback theory, feedback links between the surface and the overlying air are such that the observed surface temperature is a good indicator of the air humidity over the surface (Granger, 1997). It is applicable to both short and tall canopies, because the VPD-VP^*_{Ts} relationship does not depend on the cover type. However, it does not distinguish between vegetated and non vegetated surfaces having the same surface roughness, temperature and air humidity, unless they have a different albedo leading to a different R_n. Its operational use thereby requires a careful land use mapping. There are other more sophisticated approaches to estimate AET from T_s, like soil-vegetation-atmosphere transfer (SVAT) models (see the review in Olioso et al. (1999)). SVAT models usually require a high number of input variables and thereby have little operational potentials in fire management.

2.3. Synergisms between optical and thermal infrared remote sensing

Several empirical studies already showed that inclusion of thermal infrared data improved correlations between NDVI-related indices and drought-related variables (Dominguez et al., 1994; Chuvieco et al., 1999b, 2003; Aguado et al., 2003; Oldford et al., 2003; Oldford et al., 2006; Leblon et al., 2007). Oldford et al. (2006) showed that for slow-drying fuel moisture code (DC) mapping, compared with weather station data interpolation, improved spatial resolution can be achieved at the pixel level when DC is computed using a regression model which has surface temperature and NDVI NOAA-AVHRR images sensing data as independent variables (Figure 3). The fire shown in the center of the 15x15 pixel area was classified by the Sustainable Resource Development Department of Alberta as a surface fire, caused by lightning. It is interesting to observe that the fire burned in a closed coniferous forest cover type which was classified as having a high DC danger rating, when the NOAA-AVHRR image was used, but it was classified as having a moderate DC danger rating in the weather station-based map.

Combining optical vegetation indices with surface temperature data helps account for the influence on the ground cover rate over the composite surface temperature measured by the sensor. This led to defining several drought indices, like the Vegetation and Temperature Condition Index (VT) (Kogan, 2001), an empirical index (Chuvieco et al., 2003), the Water Deficit Index (WDI) (Vidal and Devaux-Ros, 1995), and the Temperature-Vegetation Wetness

Index (TVWI) (Akther and Hassan, 2011). WDI was related to the number of fires and the area burned in the case of Mediterranean forests (Vidal and Devaux-Ros, 1995). TVWI together with the surface temperature and the normalized multiband drought index were related to fire occurrence maps in the case of boreal forests (Akther and Hassan, 2011). The inverse relationship between NDVI and T_s was related to fire occurrences in Mediterranean forests (Prosper-Laget et al., 1994) and to moisture-related variables, such as canopy resistance (Nemani and Running, 1989), sensible and latent heat flux (Nemani and Running, 1989; Olioso et al., 1999), leaf water potential (Goward et al., 1994), accumulated rainfall (Duchemin et al., 1999), FWI codes and indices (Dominguez et al., 1994; Aguado et al., 2003, Oldford et al., 2006; Leblon et al., 2007), and foliar moisture content (Chuvieco et al., 1999b, 2003).

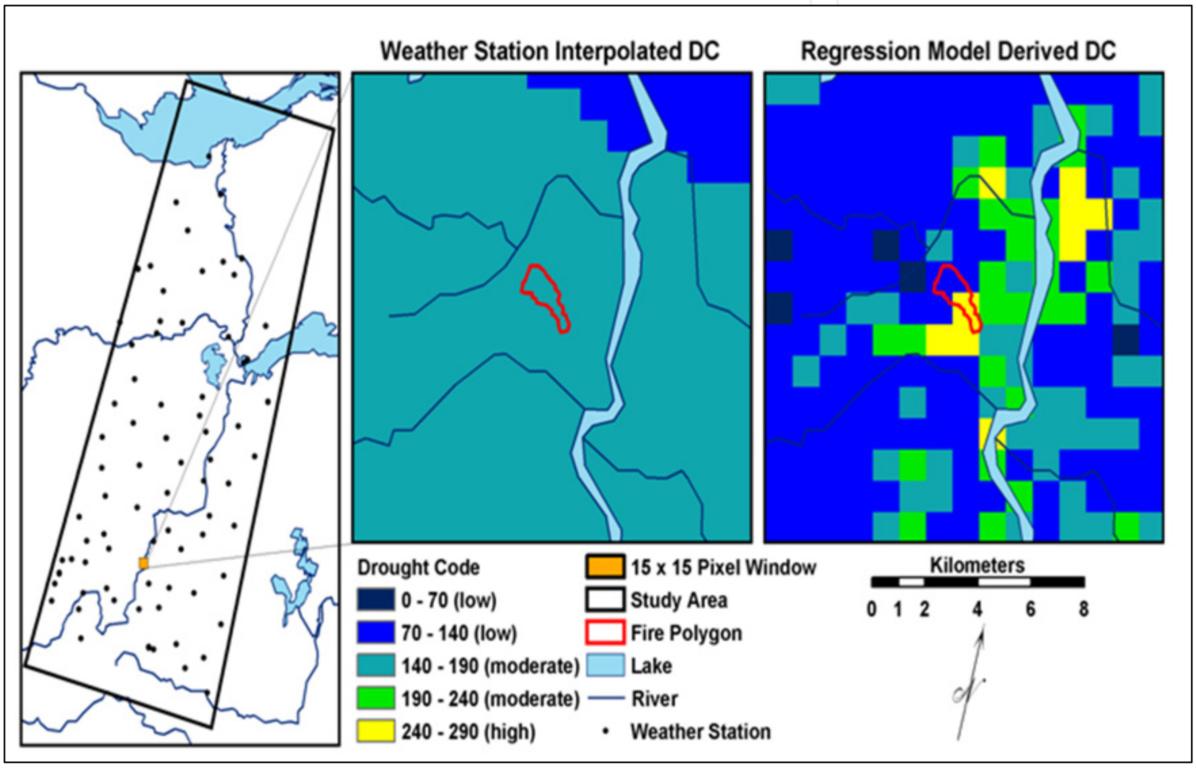


Figure 3. Comparison between a slow-drying fuel moisture code (DC) mapped by weather station interpolation and the one computed by stepwise multiple regression models from NOAA-AVHRR images for the June 1- June 10 1995 compositing period. The fire polygon corresponds to a 62 ha area burned between 2 and 17 June 1995 (after Oldford et al., 2006)

Other synergisms between optical and thermal infrared data can also be considered when estimating AET using the energy budget equation. Indeed, the required net radiation flux (R_n) can be computed from the solar irradiance at the surface or from the surface albedo, both variables being inferred from optical data (e.g., Granger, 1997; Bastiaanssen et al., 1998). Also, the ratio between the soil heat flux (G) and R_n can be analytically derived from optical vegetation indices (e.g., Bastiaanssen et al., 1998; Leblon, 2005).

Using both thermal infrared and NDVI images improve the correlation with fuel moisture variables, but these images have the same operational inconvenience of limited image availability during cloudy days. As reviewed in Leblon (2005), many strategies can be applied to overcome the problem of cloudy days, like the interpolation of evaporation fractions for the cloudy days, or the use of images acquired by passive or active microwave sensors, which are able to penetrate cloud cover. Currently, only the SSM/I sensor provides images acquired in passive microwaves, but at a coarser spatial resolution than NOAA-AVHRR images. For all these reasons, this paper has no further discussion of the use of passive microwaves in fuel moisture monitoring. By contrast, active microwave (or radar) images can be acquired by several existing satellites, i.e., ERS-1/2, ENVISAT, and RADARSAT-1/2, ALOS-PALSAR. In addition to acquiring images under all illumination and weather conditions, these satellites provide data at a finer spatial resolution than NOAA-AVHRR.

2.4. Radar remote sensing

Studies reviewed in Leblon et al. (2002) and in Abbott et al. (2007) have shown that radar backscatter ($\sigma°$) measurements over forested areas depend on (i) vegetation type, species, and structure, (ii) vegetation biomass, (iii) topography and surface roughness and canopy height; (iv) flooding and the presence/absence of standing water, and (iv) moisture. Three sources of moisture variation may contribute to the forest radar backscatter: the forest floor, the canopy (including its woody elements) and the environmental conditions (rain events). Over boreal forests, positive relationships between radar backscatters and rainfall amounts were found with ERS-1 C-VV SAR images (Bourgeau-Chavez et al., 1999; Leblon et al., 2002) and with RADARSAT-1 C-HH SAR images (Abbott et al., 2007). The good correlation between $\sigma°$and weather variables, which are used to compute the various FWI codes and indices, may expect that these indices and codes are also well related to $\sigma°$. FWI codes and indices were correlated to $\sigma°$ derived from ERS-1 C-VV and RADARSAT-1 C-HH SAR images acquired over burned and unburned boreal forests located in Alaska (Bourgeau-Chavez et al., 1999; 2001, 2006, 2007) and in the Northwest Territories, Canada (Leblon et al., 2002; Abbott et al., 2007) (Figure 4).

While these studies produced encouraging results, they also showed that single channel C-band SAR images are restricted in their applicability across the landscape primarily due to variations in surface roughness and biomass which act as confounding factors. Recently, fully polarimetric X-, C- and L-band SAR sensors have been launched into orbit (ALOS-PALSAR in 2006 and TerraSAR-X and RADARSAT-2 in 2007) allowing for decomposition of the backscattered energy into dominant scattering mechanisms which may prove useful for reducing the confounding factors and allowing improved extraction of the variable of interest in the absence of ancillary information.

Bourgeau-Chavez et al. (2012) compared RADARSAT-2 polarimetric SAR images acquired under the same incidence angle and during an extreme dry date and a wet date over a chronosequence of Alaskan boreal black spruce ecosystems (recent burns, regenerating forests dominated by shrubs, open canopied forests, moderately dense forest cover). They found that there was a significant difference between the wet and the dry dates for all backscatter polarizations and for the Freeman-Durden (Freeman and Durden, 1998) and van Zyl decomposition (van Zyl et al., 2011) parameters particularly for the parameter corresponding to odd bounce or surface scatters (Table 1). However, none of the Cloude-Pottier decomposition (Cloude and Pottier, 1997) parameters exhibited significant differences between the wet and dry dates. Indeed, the Cloude-Pottier decomposition works with the polarimetric state only, and does not consider the span information (i.e., radar intensity) in contrast to the two other decompositions. Both use intensity information implicitly and therefore more information from the imaged area. These polarimetric decomposition parameters are currently under investigation in empirical algorithm development for a multi-date dataset (across a range of soil moisture conditions) over the Alaska boreal test area.

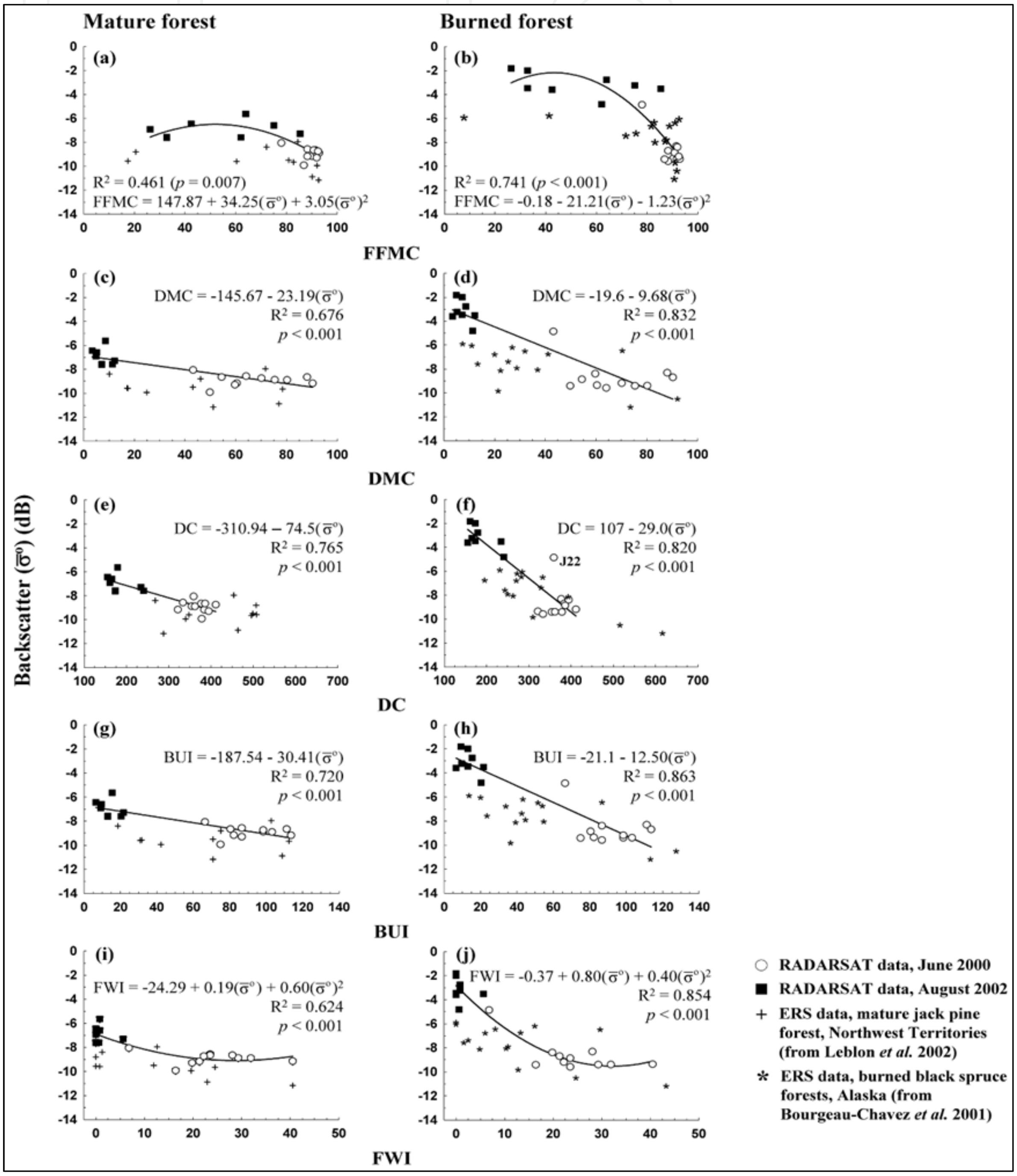


Figure 4. Relationship between ERS-1 C-VV SAR and RADARSAT-1 C-HH SAR radar backscatters (σ^o) and Fire Weather Index (FWI) codes and indices over boreal forest sites in the Northwest Territories, Canada and in Alaska, USA (data from Bourgeau-Chavez et al., 2001; Leblon et al., 2002; Abbott et al., 2007)

Parameter	*p-value*
C-HH backscatter	0.000
C-HV backscatter	0.031
C-VV backscatter	0.000
C-RR backscatter	0.000
C-LR backscatter	0.005
C-LL backscatter	0.020
Cloude-Pottier Alpha	0.698
Cloude-Pottier Anisotropy	0.577
Cloude-Pottier Entropy	0.609
Freeman Durden Double Bounce	0.052
Freeman Durden Odd Bounce	0.005
Freeman Durden Volume Scatter	0.020
van Zyl Double Bounce	0.003

Table 1. *P-value* of the one way ANOVA test for wet vs. dry conditions by SAR parameter measured over several sites of a chronosequence of Alaskan boreal black spruce ecosystems (recent burns, regenerating forests dominated by shrubs, open canopied forests, moderately dense forest cover) (after Bourgeau-Chavez et al. 2012)

Although radar images are theoretically available independently of the weather conditions, their availability could be limited because of the longer repeat cycle of the satellites. For example, ERS-1/2 had a repeat cycle of 35 days. Fortunately the revisit period is shorter for the Canadian radar satellites (RADARSAT-1/2), which has a possible quasi-daily coverage due to its pointing capability (Abbott et al., 2007). In addition, often the radar images have a finer spatial resolution than optical or thermal infrared images, while covering a smaller area. Thus, radar data represent a data source that is complementary to optical or thermal infrared data. Consequently, synergisms between optical or thermal infrared bands and radar bands should be investigated.

3. Fire detection and burnt area mapping

Fire detection is one critical stage of wildfire management, which is aimed at either fighting or monitoring the fire. For fire fighting the early detection is essential; so far, fire detection for fire fighting is based on human observation, the use of fixed optical cameras to monitor the surrounding environment, or aerial survey. The revisit time provided by current satellite sensors is not considered sufficient for fire fighting operations by forest fire mangers. However, the monitoring of wildfires and wildfire effects for large territories is mainly based on satellite remote sensing. Mapping of burnt areas and assessment of wildfire effects is one of the most successful applications of satellite remote sensing. Satellite remote sensing provides the means for acquiring comprehensive and harmonized information on wildfire effects for large territories at low cost. For this purpose, burnt area mapping is performed with a wide variety of remote sensors and techniques. A wide variety of optical and radar sensors have been used for fire detection and burnt area mapping, from local to global scales. This section reviews the application of remote sensing in active fire detection and the assessment of fire damages through the mapping of the extent of burnt areas.

3.1. Fire detection

Fires produce anomalies that are detectable in many different parts of the electromagnetic spectrum and are therefore suitable for detection with the use of remote sensing techniques. Although fire detection is possible in the microwave range of the spectrum, these techniques are not used operational because of the high cost of the sensors and the low nominal achievable spatial resolution of the detection (Kempka et al., 2006). Therefore the focus of this section is on the detection of fires from optical remote sensors.

Firstly, active fires can be detected from the light they emit in the visible part of the spectrum; however, the discrimination of the fire-emitted light is only possible at night (Cahoon et al., 1992, Elvidge, 2001). Since most of the fires occur and have their highest intensity during the day, the detection of them solely at night is not of high interest for operational fire management.

Secondly, fires can be detected by the smoke plume they produce (Figure 5). This detection method is widely used at local scale, as an alternative to visual detection by human operators. Image processing algorithms can be used to single out this smoke plume in contrast to its background, and associate it to a fire. Although these systems eliminate false alarms produced by overheating of ground areas, they also present some limitations. The limitations arise from two facts; first, the smoke plume can only be detectable some time after the fire has started; and second, smoke is often conducted along the surface and emerges in an area different from that where the fire started. Ground automatic detection systems can make use of cameras mounted in towers, buildings or masts with good visibility of the surveyed terrain. The cameras can be fixed (attached to the structure) or mounted on a positioning system to vary the azimuth and elevation angles. A positioning system can be used to survey the entire environment by varying automatically the scanning angles. The detection delay depends on the scan velocity given by the motors and the optical system in the camera, noting that the image processing requirements for automatic detection are higher when using mobile sensors. The sensor technologies used in today's automatic ground detection systems are mainly infrared and visual cameras (San-Miguel-Ayanz et al., 2005).

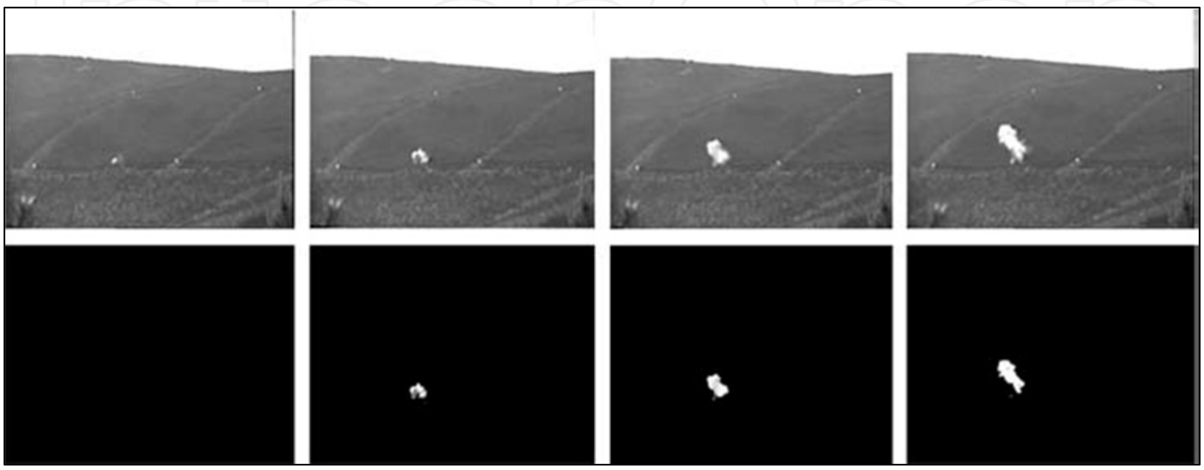


Figure 5. Smoke plume identification for fire detection with optical cameras

Lastly, and most commonly, fires are detected due to the distinct high temperature they produce, which results in a high reflection signal in the mid-infrared and thermal electromagnetic spectra. Active fires produce temperatures ranging between 800 K and 1200 K, although they can reach up to 1800 K. These temperatures are easily detectable in the mid-infrared part of the spectrum (Matson and Dozier 1981). This mid-infrared spectral window is suitable for fire detection because it is far from the peak of the Earth and Solar radiations at 0.5 and 9.7 μm, respectively (Figure 6). Fires also radiate in the thermal part of the spectrum, i.e. between 8 μm and 12 μm; however, the peak radiation at these wavelengths corresponds to a normal environmental temperature of 300 K. Fires can be detected as local or absolute maximum in the mid-infrared and thermal spectra. An absolute (or regional) maximum is used in the so-called thresholding algorithms. Any area above a given threshold temperature is considered a fire. However, differences in fire characteristics among regions in the world lead to problems of false alarms and/or missed fires using this method. Although fixed thresholding algorithms were used in the past most current techniques fore fire detection make use of the so-called contextual algorithms. Contextual algorithms detect local maxima. Multispectral criteria are aimed at detecting the difference between a fire pixel (active fire) and the background temperature (environmental temperature in the proximity of the fire pixel (Flasse and Ceccato, 1996, Giglio et al., 2003).

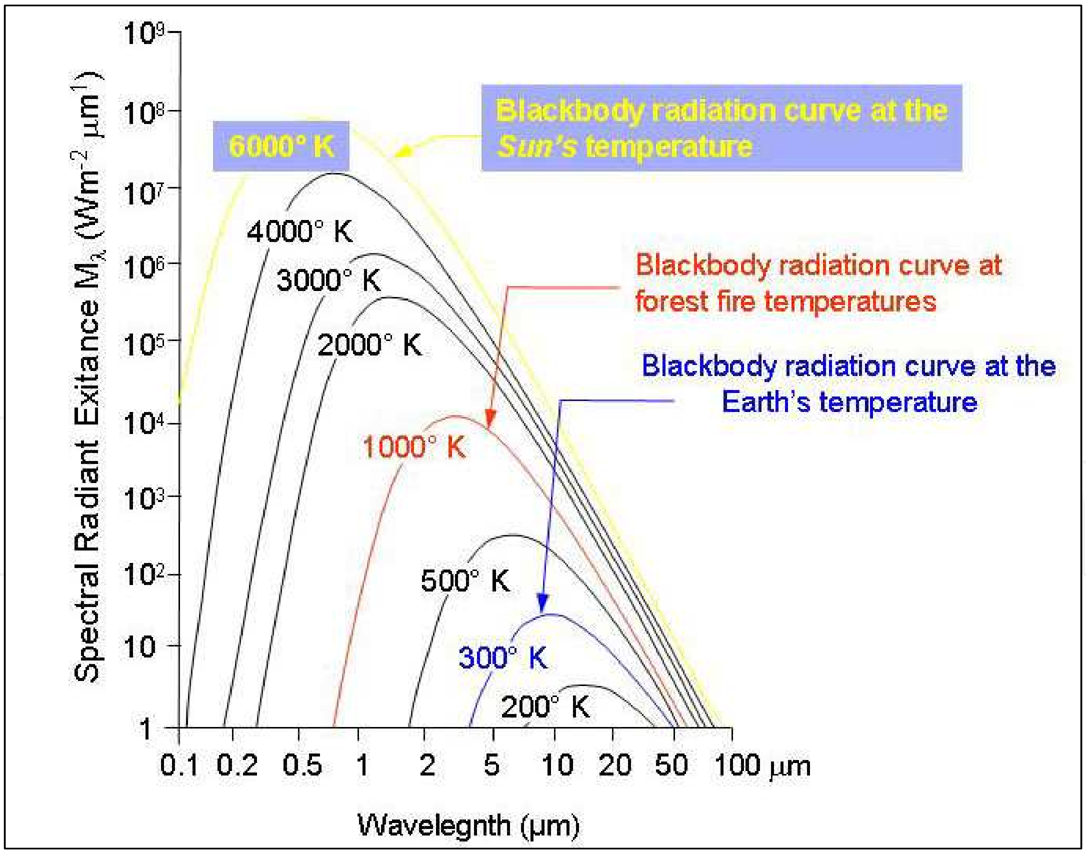


Figure 6. Spectral radiant exitance as a function of the temperature of the black body. The figure shows that forest fires being hotter than the Earth's surface exhibit a peak in their spectral exitance at a shorter wavelength than the Earth's surface

Active wildfire monitoring is performed through the use of geo-stationary satellite sensors such as GOES (Geostationary Operational Environmental Satellite) or SEVIRI on board of the Meteosat Second Generation (MSG) satellite, or geo-synchronous satellite sensors such as the AVHRR on board of the NOAA meteorological satellite, the ATSR (Along Track Scanning Radiometer) on board the ERS-1 and 2 and the Envisat, and the MODIS (Moderate Resolution Imaging Spectroradiometer) on board of the Terra and Aqua satellites.

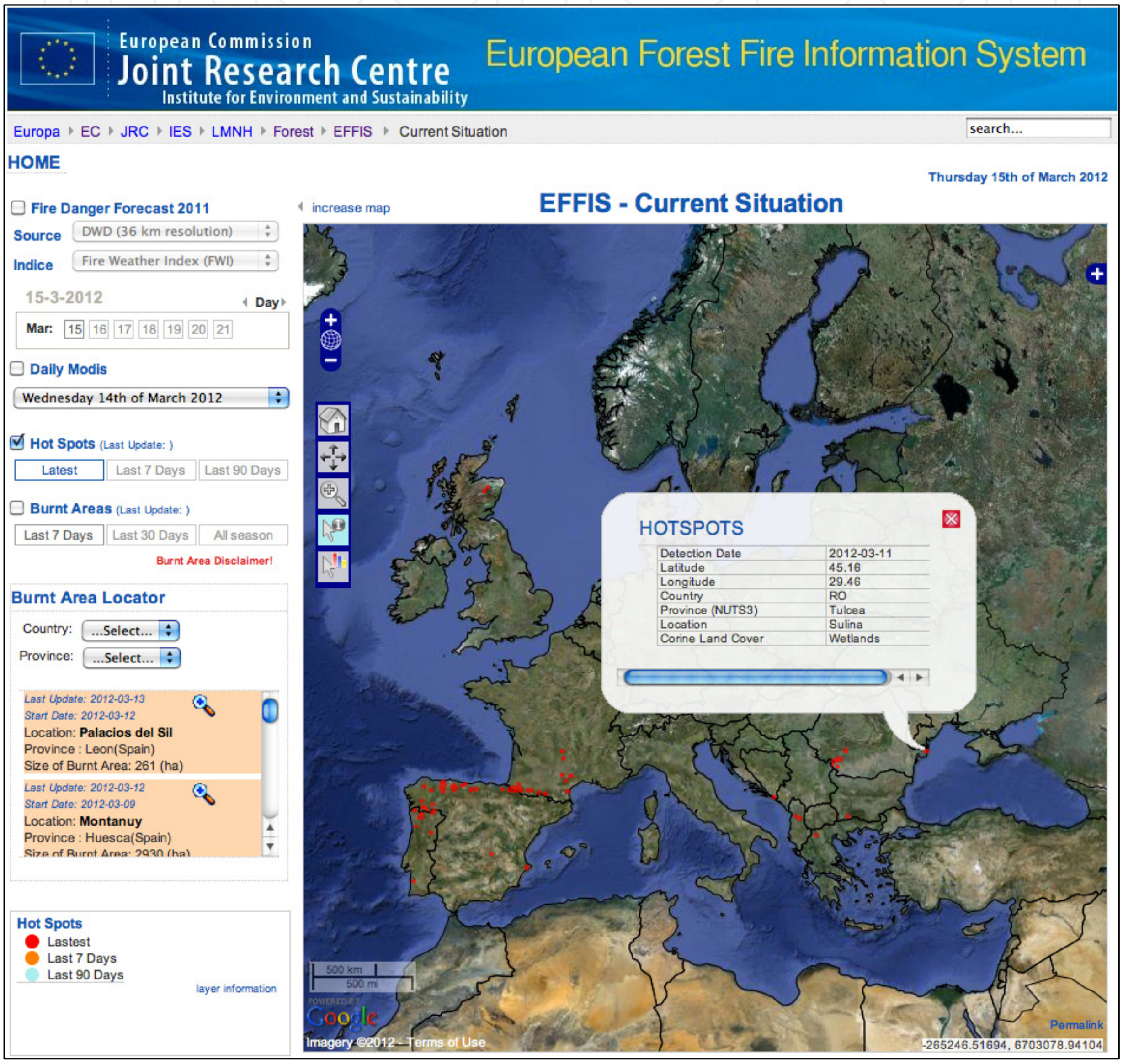


Figure 7. MODIS-based active fire detection in the European Forest Fire Information System (EFFIS) (http://effis.jrc.ec.europa.eu)

GOES and SEVIRI provide high frequency coverage in the order of 30 minutes and 15 minutes, respectively. They are thus suitable for the monitoring of most wildfire processes

(Prins and Menzel, 1992; Prins et al., 1998). This is a relative advantage for the monitoring of fire activities, as compared to ATSR, AVHRR that provide a maximum of 1 daily pass, or MODIS, which provides 2 daily passes. However, due to its high spatial resolution, its good fire detection capabilities and its global coverage, MODIS has become the standard sensor for active fire monitoring at regional to global scales. The Aqua MODIS instrument acquires data twice daily (1:30 PM and AM), as does the Terra MODIS (10:30 AM and PM). These four daily MODIS fire observations serve to advance global monitoring of fire processes and their effects on ecosystems, the atmosphere, and climate (Giglio et al., 2006a and 2006b). Some operational fire monitoring systems using MODIS active fire detection include the Canadian Wildland Fire Information System (CWFIS) (http://cwfis.cfs.nrcan.gc.ca), the USA Active Fire Mapping Service, or the European Forest Fire Information System (EFFIS) (http://effis.jrc.ec.europa.eu). In the case of EFFIS, post-processing filters based on landcover ancillary data are applied to the MODIS product to reduce the number of false alarms produced by non-fire hot surfaces (e.g. industrial areas, hot ground soils) and therefore increase the reliability of the active fire detection (San-Miguel-Ayanz et al., 2012). Figure 7 shows operational fire detection monitoring in the European region within EFFIS.

3.2. Burnt area mapping

Remotely sensed data have been extensively used for burnt area mapping. Fires produce a significant change in the structure and the reflectance of vegetation and the soil properties within the burnt area that are noticeable in the microwave, visible and especially the infra-red part of the electromagnetic spectrum.

At the global scale, NOAA-AVHRR data were extensively tested in the 1990s. Studies differed mainly on the use of diverse spectral indices, although most commonly, burn scar areas were discriminated from a multi-temporal comparison of NDVI (Kasischke and French, 1993; Martin and Chuvieco, 1995; Pereira, 1999). More recently other global burnt area datasets were derived from SPOT Vegetation and the ATSR-2 on board of Envisat (Gregorie et al., 2003, Tansey et al., 2004; Simon et al., 2004). Although these data provide gross estimates of burnt areas at the global level, the lack of extensive validation and agreement between them limit their use at regional or national levels. Nevertheless, partial validations of the global burnt area products were performed by Roy et al. (2005) and Boschetti et al. (2007). Pereira et al. (1999) showed that the accuracy of the results for mapping burnt areas with AVHRR data in the Mediterranean region of Europe was about 80% for large fires. The methods were considered suitable only for fires larger than 1000 ha, and reliable for fires larger than 2000 ha. However, the mapping of those fires would correspond only to approximately 30% and 21%, respectively, of the total yearly burnt area in the European Mediterranean region.

With the launch of the MODIS sensor on board of the TERRA and AQUA satellites, a new capability for regional mapping of burnt areas was put in place. The availability of free data of medium spatial resolution from the MODIS sensors since 2000 provided a definite impulse for the use of remote sensing at the regional and global scales (Justice et al, 2002). Better radiometry and higher spectral information of the MODIS sensor provided the right data for the discrimination of burnt areas at these scales. The simultaneity in the operation of both satellites provided higher frequency in data acquisition and enough revisit time for accurate mapping of burnt areas. At the global scale, the MODIS program has released a standard product on burned areas that is based on a multitemporal change detection approach to analyze differences between modeled and actual reflectance, and to take into account Bidirectional Reflectance Distribution Function (BRDF) corrections (Roy et al., 2002, 2005).

At regional scale, MODIS is operationally used in systems such as Canadian CWFIS and the European EFFIS, mentioned above. Two full mosaics of MODIS data are received and processed daily in EFFIS to provide near-real time monitoring of wildfires and map burnt areas. The systems is thus updated up to two times daily, providing accurate information of fire impacts in Europe ((San-Miguel-Ayanz et al. 2009). The use of higher spatial resolution imagery from Advanced Wide Field Sensor (AWiFS) for regional coverage in Europe was recently tested. However, results of this exercise showed that the benefits derived from the use of high spatial imagery in term of detailed mapping of fire perimeters are obscured by the limitations in the revisit time of the sensor. These results did not enhance those of the standard Rapid Damage Assessment module of EFFIS based on MODIS imagery (Sedano et al., 2012). Figure 8 shows the extent of burnt area as they were mapped from MODIS and AWIFS imagery.

At national to local scales, the wide variety of remotely sensed products at medium to high resolution (10 m to 30 meter ground spatial resolution), make it possible the accurate mapping of burnt areas. However, the increase in spatial resolution is often accompanied by a decrease in revisit time of the sensor, which prevents the acquisition of this imagery for extensive areas.

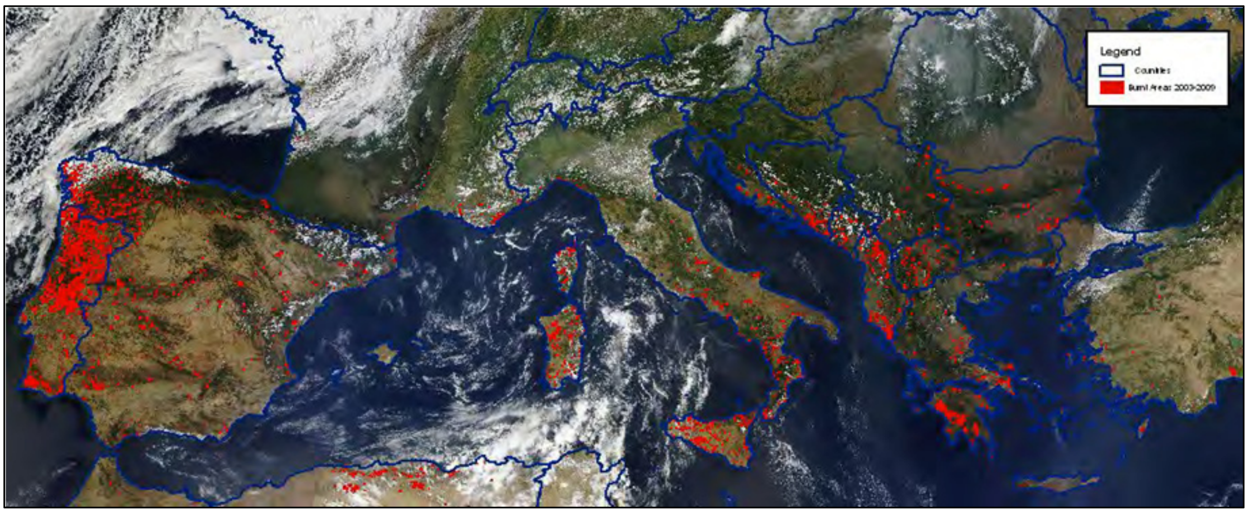


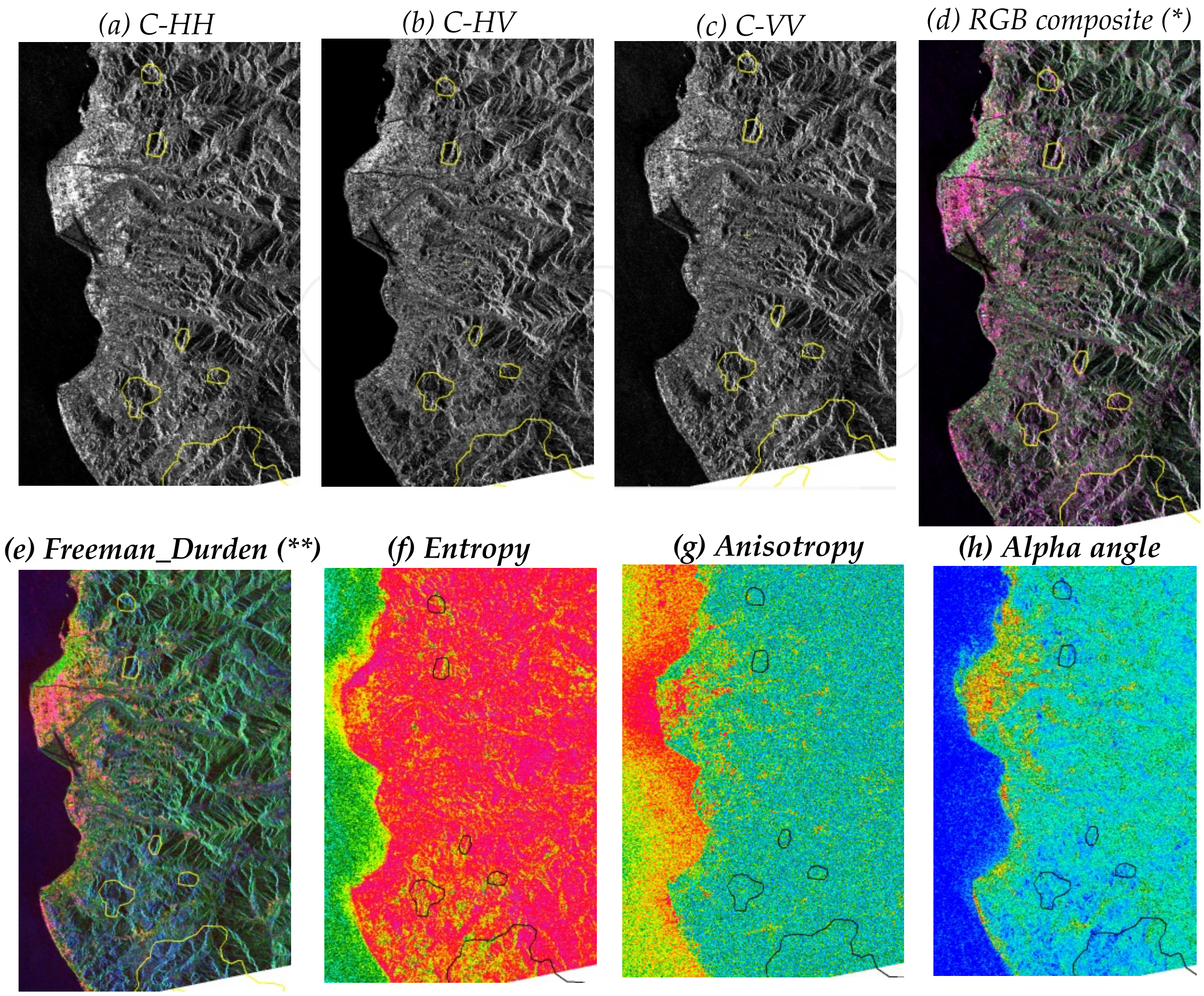
Figure 8. Burnt areas in the European Mediterranean region between 2000 and 2009 (http://effis.jrc.ec.europa.eu)

High-spatial burnt area mapping has been performed with Landsat Thematic Mapper imagery (Michalek et al. 2000, Pereira and Setzer, 1993, Chuvieco and Congalton, 1998) complemented in some cases by the SPOT and ASTER sensors. Some analyses made use of the LISS-3 sensor of the IRS Indian satellite, and the RESURS MSU-K (San-Miguel-Ayanz et al, 1998). A variety of indices computed from the original spectral bands were used to enhance the mapping of burnt areas (Pereira et al., 1997, Li et al. 2000, Chuvieco et al, 2002). However, this exercise was, in most cases, limited to the mapping of burnt areas at local and sub-national scale. An exception to this is the case of Portugal, where an operational system capable of processing Landsat TM scenes for mapping of burnt areas was set up (Pereira et al., 1993).

The use of high resolution remote sensing in the management of critical wildfires has improved dramatically in the last decade. The variety of remote sensing imagery of high and very-high spatial resolutions such QUICKBIRD, IKONOS, FORMOSAT, EARLYBIRD, RAPIDEYE has permitted the rapid coverage of critical fire events. The processing of this imagery provides a great level of spatial detailed that is needed for the accurate analysis of fire damages and the sound planning of restoration measures. Data provision for critical fire events has been supported by the agreement of the space agencies in the so-called International Space Charter, which allows the rapid provision available remotely sensed data from a series of satellites, including RADARSAT, ERS, ENVISAT, SPOT, IRS, SAC-C, NOAA satellites, LANDSAT, ALOS, DMC supporting crisis management.

Although most of the studies on burnt area mapping were based on the use of optical imagery, there are a series of examples in which data from active sensors such as the Synthetic Aperture Radar (SAR) were used. Most of the studies were carried out in boreal forest (Bourgeau-Chavez et al. 1997, 2002, Kasische et al, 1994, French et al. 1999, Siegert and Ruecker, 2000, Menges et al, 2004), but some examples for the Mediterranean area exist (Gimeno and San-Miguel-Ayanz, 2004, Gimeno et al. 2005). Rather than the changes in vegetation condition and structure, the detection of burnt areas from SAR is based on the changes on moisture content in the burnt surface with respect to the unburned areas. Burnt areas tend to have higher moisture content than unburned areas, which reduces the backscatter. Thus, burnt areas appear as dark objects in relation to the surrounding non-affected areas.

Similarly to the studies on pre-fire conditions (see Section 2), polarimetric SAR images have been recently tested. They were more efficient for fire detection and burnt area mapping than single channel C-band SAR images. Figure 9 compares RADARSAT-2 single-polarized and polarimetric SAR images that were acquired at 32.4°-34° incidence angle and using a east-looking direction, during a dry day, between 1 to 2 months after fires that occur in rough terrains (Calabria peninsula in Southern Italy). Similar to the pre-fire conditions study (see Table 1), fire scars were more visible on the Freeman-Durden decomposition images than on the Cloude-Pottier decomposition, probably because the first decomposition works with the polarimetric state only, and does not consider the span information (i.e., radar intensity) in contrast to the second one. The Freeman-Durden decomposition uses more information from the imaged area because it implicitly considers the intensity information.



(*)HH in red, HV in green and VV in blue; (**) double-bounce in red, volume in green and surface in blue

Figure 9. Fire scars over various RADARSAT-2 products made from a RADARSAT-2 that was acquired over Calabria peninsula in Southern Italy 1 to 2 months after the fires during a dry date using an ascending pass (east-looking direction) with a FQ13 beam mode (32.4°-34° incidence angle). The fire scar limits are displayed in yellow or black.

4. Conclusions

We reviewed studies using optical, thermal infrared and radar images for pre-fire and post-fire conditions monitoring. For the pre-fire conditions, our review has a particular emphasis on the studies using satellite data to monitor fuel moisture. Remote sensing of fuel moisture was first done with NDVI images (mainly from NOAA-AVHRR), based on the assumption that the greenness of the scene is a good indicator of fuel moisture and fire danger. NDVI images are used operationally to map fire potentials, but the reviewed studies have shown that NDVI is sensitive to the chlorophyll activity of the vegetation rather than to its actual changes in moisture content. By contrast, thermal infrared images allow the computation of surface temperatures which are analytically related to surface moisture-related variables, like evapotranspiration, through the energy budget equation. This analytical approach was used to compute the ratio between actual and potential evapotranspiration (AET/PET) from daily surface temperatures and synoptic air temperatures. The ratio was used in an operational fire danger monitoring system over Mediterranean forests. The same ratio was computed from optical and thermal infrared images acquired over Canadian northern boreal forests and related to FWI codes and indices. In the AET/PET computation, NDVI images were also used, in the calculation of soil heat flux and aerodynamic resistances.

More recent studies on the use of remote sensing in fuel moisture monitoring use both NDVI and surface temperature images. This is done at no additional cost of data acquisition, since both kinds of images are provided in the same time by numerous existing satellites, like NOAA-AVHRR, LANDSAT-TM, ATSR-2, RESURS-01, METEOSAT, GOES, EOS-ASTER, and EOS-MODIS. An important operational limitation of using optical and thermal infrared data is image availability, which still depends on weather and illumination conditions. For this reason, an operational system to monitor fuel moisture using satellite images should probably also include radar images, which can be acquired during cloudy days. These images have also the advantage of having a finer spatial resolution.Good relationships were found between ERS-1 and RADARSAT-1 radar backscatters and FWI codes and indices over northern boreal forests, but these studies also showed that radar backscatters are affected by several confounding factors other than those related to moisture, such as surface roughness and biomass. More recently, the availability of polarimetric SAR images allows for decomposition of the backscattered energy into dominant scattering mechanisms which may prove useful for reducing the confounding factors. Statistically significant differences between wet and dry dates were observed in the case of several polarimetric variables extracted from RADARSAT-2 C-band polarimetric SAR images, such as the Freeman-Durden and van Zyl decomposition parameters particularly for the parameters corresponding to odd bounce or surface scatters. Further studies are required to establish models that can use such data for estimating fuel moisture.

One limitation of the operational use of SAR images in fire danger monitoring is image availability that is limited by the long revisit periods of most existing radar satellites and by the commercial operating mode of some new radar satellites, like RADARSAT-2. However, the availability in the near future of SAR satellite constellations such as the planned RADARSAT-3 mission, will decrease the revisit period. Eventually, further studies are needed to assess the combination of optical and thermal infrared images to radar images for monitoring pre fire conditions.

Most of the reviewed remote sensing studies for pre-fire conditions management are based on the estimation of fuel moisture which is one of the canopy factors which influences fire danger. However, further research is needed to see whether or not current fire danger rating systems can account for canopy variables, like evapotranspiration or moisture content, which are more closely related to spectral variables. On the other hand, all required input variables of an operational fire danger system, like wind parameters, will surely not be derived from remote sensing data and additional ground-based and weather information will always be required to effectively monitor fire danger. In this regard, *in situ* sensing systems, as described in Teillet et al. (2001), will be useful.

Regarding fire detection, remote sensing techniques can be considered fully operational. At local scale they are mainly based on the use of visible and infra-red cameras for the detection of active fires or smoke plumes. Fire detection at this scale is focused on support to forest fire fighting operations. At large scale, information is provided by geo-stationary satellite sensors (GOES, SEVIRI) or geo-syncronous sensors (AVHRR, ATSR, MODIS). The high revisit time of the geostationary satellites provide frequent information (15 to 30 minutes) that is indicated for monitoring fire processes and fire effects. However, although geo-stationary satellites provide a lower revisit time (1 to 2 daily passes), they provide global fire information that is essential for the monitoring of wildfire processes and their effects on ecosystems, the atmosphere, and climate.

Burnt area mapping from remote sensing has been on-going for nearly 30 years. Most of these applications are based on passive optical remote sensing imagery at global and regional scales. Global burn area datasets were derived from AVHRR, ATRS, Vegetation, and recently from MODIS. At local scale, actives sensors such as the ERS SAR and RADARSAT have proven their capacity for monitoring fires under all-weather conditions. Currently, the data acquired by the MODIS sensor has become the standard for fire monitoring at regional to global scales and is used for environmental policy and decision-making. At local level, numerous examples on the use of high-spatial resolution imagery exist. However, the lack of operational routines for the processing of satellite imagery and the difficulties in acquiring cloud free imagery due to the low revisit time of the sensors has prevented the full operationalization of remote sensing. Agreements have been recently established among the Space Agencies in the International Space Charter for the provision of remote sensing data for wildfire crisis management, which permits the rapid monitoring of critical fire events.

Author details

Brigitte Leblon and Laura Bourgeau-Chavez
Faculty of Forestry and Environment Management,
University of New Brunswick, Fredericton, New Brunswick, Canada

Jesús San-Miguel-Ayanz
Forest Resources and Climate Unit, Institute for Environment and Sustainability, Ispra, Italy

Acknowledgement

The pre-fire conditions study is a compendium of the works from the following students: Lisa Gallant, Shannon White, Mark Doyle, Melissa Abbott, Guy Strickland, Keith Abbott, Steven Oldford and P.A Fernandez-Garcia. ERS-1 and RADARSAT-1 SAR image processing were helped by N. French and Gordon Staples Field support for the RADARSAT-2 study was provided by Aditi Shenoy, Eric Kasischke, Kevin Riordan, Kristen Manies, and Nancy French. The whole study was funded by CIFFC, MacDonald, Dettwiler and Associates Ltd. (MDA)and by a NSERC Discovery grant awarded to B. Leblon. Additional funding for this research was provided by NASA grants NNX09AM15G and NNG04GR24G. NOAA-AVHRR images were provided under the EODS program, thanks to J. Cihlar and J. Chen, Canada Centre of Remote Sensing, Ottawa. ERS-1 SAR images were provided by E.S. Kasischke. RADARSAT-1 images were acquired under the ADRO-2 program of the Canadian Space Agency. RADARSAT-2 polarimetric images were provided by a Canadian Space Agency SOAR grant (SOAR#445). Weather data were obtained from Marty Alexander, Canadian Forest Service, Edmonton and Rick Lanoville, Government of Northwest Territories, Fort Smith. Examples for the sections on active wildfire detection and burnt area mapping were extracted from the European Forest Fire Information System (EFFIS). This is the result of a team of scientists working in different fire-related disciplines at the at the European Commission Joint Research Centre (http://effis.jrc.ec.europa.eu)

5. References

Abbott, K., Leblon, B., Staples, G., Alexander, M.E., & MacLean, D. (2007). Fire danger monitoring in a northern boreal forest region using RADARSAT-1 imagery. *International Journal of Remote Sensing,* Vol. 28, No 5-6, (March 2007), pp. 1317-1338, ISSN 0143-1161

Aguado, I., Chuvieco, E., & Salas, J. (2003). Assessment of forest fire danger conditions in southern Spain from NOAA images and meteorological indices. *International Journal of Remote Sensing,* Vol. 24, No 8, (January 2003), pp. 1653-1668, ISSN 0143-1161

Akther, M. S., & Hassan, Q. K. (2011). Remote sensing-based assessment of fire danger conditions over boreal forest. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Vol. 4, No. 4, (December 2011), pp. 992-999, ISSN 1939-1404.

Bastiaanssen, W.G.M., Menenti, M., Fedded, R.A., & Holtslag, A.A.M. (1998). A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. *Journal of Hydrology,* Vol. 212-213, (December 1998), pp. 198-212, ISSN 0022-1694.

Boschetti, L., Roy, D., Barbosa, P., Boca, R., & Justice, C. (2008). A MODIS assessment of the summer 2007 extent burned in Greece. *International Journal of Remote Sensing*, Vol. 29, No 8, (April 2008), pp. 2433-2436, ISSN 0143-1161

Bourgeau-Chavez, L.L., Harrell, P.A., Kasischke, E.S. & French, N.H.F. (1997). The detection and mapping of Alaskan wildfires using a spaceborne imaging radar system. *International Journal of Remote Sensing*, Vol. 18, No 2, (January 1997), pp. 355-373, ISSN 0143-1161

Bourgeau-Chavez, L.L., Kasischke, E.S., & Rutherford, M.D. (1999). Evaluation of ERS SAR data for prediction of fire danger in a boreal region. *International Journal of Wildland Fire,* Vol. 9, No 3, pp. 183-194, ISSN 1049-8001.

Bourgeau-Chavez, L. L., Brunzell, S., Nolan, M., & Hyer, E. (2001). Analysis of SAR data for fire danger prediction in boreal Alaska. *Final Report, ASF-IARC Grant NAS-98-129,* 59 pages.

Bourgeau-Chavez, L.L., Kasischke, E.S., Brunzell, S.M., Tukman, M. & Mudd, J.P. (2002) Mapping fire scars in global boreal forests using imaging radar data. *International Journal of Remote Sensing,* Vol. 22, No 18, (January 2002), pp. 3665-3687, ISSN 0143-1161.

Bourgeau-Chavez, L.L, Riordan, K., Garwood, G., Cella, B., Alden, S., Kwart, M., Murphy, K., Ferguson, S., Slawski, J., Medvecz, M., Ames, S.& Walters, T. (2006) Benchmark

Report on the use of Satellite radar imagery for monitoring fuel moisture in Alaska. Final report on NASA SENH project NAS5-03113. 96 pp. Available from http://aiwg.gsfc.nasa.gov/esappdocs/benchmarks/NASASENHFuelMoisture_Bench_sept06.pdf

Bourgeau-Chavez, L.L., Kasischke, E.S., Riordan, K., Brunzell, S.M., Hyer, E., Nolan, M., Medvecz, M. & Ames, S. (2007). Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery. *International Journal of Remote Sensing*, Vol. 28, No 10, (May 2007), pp. 2133-2162, ISSN 0143-1161

Bourgeau-Chavez, L.L., Leblon, B., Buckley, J., & Charbonneau, F. (2012). Assessment of polarimetric SAR data for fuel moisture estimation: Analysis of wet *versus* dry conditions. *International Journal of Remote Sensing (accepted),* ISSN 0143-1161

Burgan, R.E., Klaver, R. W., & Klaver, J.M. (1998). Fuel models and fire potential from satellite and surface observations. *International Journal of Wildland Fire,* Vol. 8, No 3, pp. 159-170, ISSN 1049-8001.

Cahoon, D. R., Jr., Stocks, B. J., Levine, J. L., Cofer III, W. R., & O'Neill, K. P. (1992). Seasonal distribution of African savanna fires. *Nature*, Vol. 359, (October 1992), pp. 812– 815, ISSN 0028-0836

Camia, A., Bovio, G., Aguado, I., & Stach, N. (1999). Meteorological fire danger indices and remote sensing. In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, E. Chuvieco Ed., , pp. 39-59, Springer-Verlag, ISBN 978-3540657675, Berlin.

Canadian Forest Service. (1992). Development and Structure of the Canadian Forest Fire Behaviour Prediction System. Canadian Forest Service, Information Report ST-X-3, Ottawa, ONT., 63 p.

Canadian Forest Service. (2012). *Forest fire facts and questions*. Available from http://cfs.nrcan.gc.ca/pages/153

Ceccato, P., Flasse, S., Tarntola, S., Jacquemoud, S., & Grégoire, J.M. (2001). Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sensing of Environment,* Vol. 77, No 1, (July 2001), pp. 22-33, ISSN 0034-4257

Chuvieco, E., & Martin, M. P. (1994). Global fire mapping and fire danger estimation using AVHRR images. *Photogrammetry Engineering and Remote Sensing,* Vol. 60, No 5, (May 1994), pp. 563-570.

Chuvieco, E., Aguado, I., Cocero, D., & Riaño, D. (2003). Design of an empirical index to estimate fuel moisture content from NOAA-AVHRR analysis in forest fire danger studies. *International Journal of Remote Sensing,* Vol. 24, No 8, (January 2003), pp. 1621-1637, ISSN 0143-1161.

Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Pilar, M., Vilar, L., Martínez, J., Martín, S., Ibarra, P., de la Riva, J., Baeza, J., Rodríguez, F., Molina, J. M., Herrera, M.A., & Zamora, R. (2010). Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling*, Vol. 221, No 1, (January 2010), pp. 46–58, ISSN 0304-3800.

Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Pilar, M., Vilar, L., Martínez, J., Martín, S., Ibarra, P., de la Riva, J., Baeza, J., Rodríguez, F., Molina, J. M., Herrera, M.A., & Zamora, R. (2010). Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling*, Vol. 221, No 1, (January 2010), pp. 46–58, ISSN 0304-3800.

Chuvieco, E., Deshayes, M., Stach, N., Cocero, D., & Riaño, D. (1999b). Short-term fire risk foliage moisture content estimation from satellite data. In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, E. Chuvieco Ed., pp. 17-38, Springer-Verlag, ISBN 978-3540657675, Berlin.

Chuvieco, E., Deshayes, M., Stach, N., Cocero, D., & Riaño, D. (1999b). Short-term fire risk foliage moisture content estimation from satellite data. In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, E. Chuvieco Ed., pp. 17-38, Springer-Verlag, ISBN 978-3540657675, Berlin.

Chuvieco, E., Salas, F.J., Carvacho, L., & Rodirguez-Silva, F. (1999a). Integrated fire risk mapping, In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, E. Chuvieco Ed., pp. 61-84, Springer-Verlag, ISBN 978-3540657675, Berlin.

Cloude, S.R., & Pottier, E. (1997). An entropy based classification scheme for land applications of polarimetric SAR. *IEEE Transactions Geoscience and Remote Sensing*, Vol. 35, No 1, (January 1997), pp. 68-78, ISSN 0196-2892.

Deblonde, G., & Cihlar, J. (1993). A multiyear analysis of the relatonsip between surface environmental variables and NDVI over the Canadian landmass, *Remote Sensing of Environment,* Vol. 7, pp. 151-177, ISSN 0034-4257.

Desbois, N., & Vidal, A. (1995). La télédétection dans la prévision des incendies de forêt, *Ingénieries- EAT,* Vol. 1, (March 1995), pp. 21-29.

Desbois, N., & Vidal, A. (1996). Real-time monitoring of vegetation flammability using NOAA-AVHRR thermal infrared data, *EARSeL Advanced in Remote Sensing,* Vol. 4, No 4, (November 1996), pp. 25-32.

Dominguez, L., Lee, B.S., Chuvieco, E., & Cihlar, J. (1994). Fire danger estimation using AVHRR images in the Prairie provinces of Canada. *Proceedings 2nd International Conference on Forest Fire Research*, Vol. 2, No 17, pp. 679-690, Coimbra, Portugal, November 1994.

Duchemin, B., Guyon, D., & Lagouarde, J. P. (1999). Potential and limits of NOAA-AVHRR temporal composite data for phenology and water stress monitoring of temperate forest ecosystems, *International Journal of Remote Sensing,* Vol. 20, No 5, (January 1999), pp. 895-917, ISSN 0143-1161.

Elvidge, C. D. (2001), DMSP-OLS estimation of tropical forest area impacted by surface fires in Roraima, Brazil: 1995 versus 1998. *International Journal of Remote Sensing*, Vol. 22, No 14, (January 2001), pp. 2661–2673, ISSN 0143-1161

Flasse S. P., & Ceccato, P. (1996). A contextual algorithm for AVHRR fire detection. *International Journal of Remote Sensing,* Vol. 17, No 2,(January 1996), pp. 419-424, ISSN 0143-1161.

Food and Agriculture Organization (FAO) (2012). *About the Global Fire Information Management System (GFIMS).* Available from http://www.fao.org/nr/gfims/about/en/

Freeman, A., & Durden, S.L. (1998). A three-component scattering model for polarimetric SAR data. *IEEE Transactions Geoscience and Remote Sensing*, Vol. 36, No 3, (May 1998), pp. 963- 973, ISSN 0196-2892

French, N. H. F., Bourgeau-Chavez, L. L., Wang, Y. & Kasischke, E. S. (1999). Initial observations of Radarsat imagery at fire-disturbed sites in interior Alaska. *Remote Sensing of Environment*, Vol. 68, No 1, (April 1999), pp. 89-94, ISSN 0034-4257

Giglio, L, Csiszar, I, & Justice, C. O. (2006a). Global distribution and seasonality of active fires as observed with the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors. *Journal of Geophysical Research-Biogeosciences*, Vol. 111, No G2, (June 2006), p. G02016, ISSN 0148–0227

Giglio, L, van der Werf, GR, Randerson, JT, Collatz, GJ, & Kasibhatla, P (2006b). Global estimation of burned area using MODIS active fire observations. *Atmospheric Chemistry and Physics*, Vol. 6, No 4, (March 2006), pp. 957-974, ISSN 1680-7316.

Gimeno, M. & San-Miguel-Ayanz, J. (2004). Evaluation of RADARSAT-1 data for identification of burnt areas in Southern Europe. *Remote Sensing of Environment*, Vol. 92, No 3, (August 2004), pp. 370-375, ISSN 0034-4257

Gimeno, M., San-Miguel-Ayanz, J. & Schmuck, G. (2004). Identification of burnt areas in Mediterranean forest environments from ERS-2 SAR time series. *International Journal of Remote Sensing*, Vol. 25, No 22, (November 2004), pp. 4873-4888, ISSN 0143-1161

Gouyet, J.F., King, C., Le Gleau, H., Malon, J.F., Phulpin, T., & Valette, J.C. (1991). Apport des données satellitaires NOAA-AVHRR dans le suivi de la végétation forestière. *Proceedings 5th International Colloquium on Physical Measurements and Signatures in Remote Sensing*, pp. 625-629, Courchevel, France, January 1991

Goward, S.N., Waring, R.H., Dye, D.G., & Yang, J. (1994). Ecological remote sensing of OTTER satellite macroscale observations. *Ecological Applications,* Vol. 4, No 2, (May 1994), pp. 322-343, ISSN 1051-0761.

Granger, R.J. (1997). Comparison of surface and satellite-derived estimates of evapotranspiration using a feedback algorithm. *Proceeding. 3rd International Workshop on Application of Remote Sensing in Hydrology*, pp. 71-81, Goddard Space Flight Center, Washington, DC, USA, October, 1996.

Grégoire, J.-M. Tansey K., and Silva, J. M. N. (2003). The GBA2000 initiative: Developing a global burnt area database from SPOT-Vegetation imagery, *International Journal of Remote Sensing*, Vol. 24, No 6, (January 2003), pp. 1369-1376, ISSN 0143-1161

Hardy, C.C., and Burgan, R.E. (1999). Evaluation of NDVI for monitoring live moisture in three vegetation types of the Western U.S. *Photogrammetry Engineering and Remote Sensing,* Vol. 65, pp. 603-610.

Illera, P., Fernandez, A., & Delgado, J.A. (1996). Temporal evolution of the NDVI as an indicator of forest fire danger. *International Journal of Remote Sensing,* Vol. 17, No 6, (April 1996), pp. 1093-1105, ISSN 0143-1161.

Justice, C., Giglio, L., Korontzi, S., Owens, J., Morisette, J. T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F., & Kaufman, Y. (2002). The MODIS fire products, *Remote Sensing of Environment*, Vol. 83, No 1–2, (November 2002), pp. 244-262, ISSN 0034-4257

Kasischke, E. S., Bourgeau-Chavez, L. L., & French, N. H. F. (1994). Observations of variations in ERS-1 SAR image intensity associated with forest fires in Alaska. *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 32, No 1, (January 1994), pp. 206-210, ISSN 0196-2892

Kasischke, E. S., French, N. H. F., Harrell P., Christensen N. L. Jr., Ustin, S. L., & Barry, D. (1993). Monitoring of wildfires in boreal forests using large area AVHRR NDVI composite image data. *Remote Sensing of Environment,* Vol. 45, No 1, (July 1993), pp. 61–67, ISSN 0034-4257

Kempka, T., Kaiser, T., and Solbach, K., 2006, Microwaves in fire detection. *Fire Safety Journal*, Vol. 41, No 4, (June 2006), pp. 327-333, ISSN 0379-7112

Kennedy, P. J., Belward, A. S., & Gregoire, J. M. (1994). An improved approach to fire monitoring in West Africa using AVHRR data. *International Journal of Remote Sensing,* Vol. 15, No 11, (July 1994), pp. 2235–2255, ISSN 0143-1161

Kogan, F.N. (2001). Operational space technology for global vegetation assessment. *Bulletin of the American Meteorological Society,* Vol. 82, No 9, (September 2001), pp. 1949-1964.

Leblon, B. (2005). Using remote sensing for fire danger monitoring. *Natural Hazards*, Vol. 35, No 3, (July 2005), pp. 343-359, ISSN 0921-030X.

Leblon, B., Chen, J., Alexander, M.E., & White, S. (2001). Fire danger monitoring using NOAA-AVHRR NDVI images in the case of northern boreal forests. *International Journal of Remote Sensing,* Vol. 22, No 14, (January 2001), pp. 2839-2846, ISSN 0143-1161.

Leblon, B., Kaschike, E.S., Alexander, M.E., Doyle, M, & Abbott M. (2002). Fire danger monitoring using ERS-1 SAR images over northern boreal forests. *Natural Hazards ,* Vol. 27, No 3, (November 2002), pp. 231-255, ISSN 0921-030X.

Leblon, B., Fernandez-Garcia, P.A., Oldford, S. MacLean, D., & Flannigan, M. (2007). Using NOAA-AVHRR cumulative indices for estimating fire danger codes in northern boreal forests. *International Journal of Applied Earth Observations and Geoinformation*, Vol. 9, No 3, (August 2007), pp. 335-342, ISSN 0303-2434

Lopez, S., Gonzalez, F., Llop, R., & Cuevas, J.M. (1991). An evaluation of the utility of NOAA-AVHRR images for monitoring forest fire risk in Spain, *International Journal of Remote Sensing,* Vol. 12, No 9, (September 1991), pp. 1841-1851, ISSN 0143-1161.

Martin, M. P., & E. Chuvieco (1995), Mapping and evaluation of burned land from multitemporal analysis of AVHRR NDVI images, *EARSeL Advanced in Remote Sensing,*Vol. 4, No 3, pp. 7– 13.

Matson, M., & Dozier, J. (1981). Identification of subresolution high temperature sources using a thermal IR sensor. *Photogrammetry Engineering and Remote Sensing*, Vol. 47, No 9, (September 1981), pp. 1311-1318.

Menges, C. H., Bartolo, R. E., Bell, D. & Hill, G. J. E. (2004). The effect of savanna fires on SAR backscatter in northern Australia. *International Journal of Remote Sensing*, Vol. 25, No 22, (November 2004), pp. 4857-4871, ISSN 0143-1161

Michalek, J.L., French, N.H.F., Kasischke, E.S., Johnson, R.D., & Colwell, J.E. (2000). Using Landsat TM data to estimate carbon release from burned biomass in an Alaskan spruce complex. *International Journal of Remote Sensing*, Vol. 21, No 2, (January 2000), pp. 323–338, ISSN 0143-1161

Nemani, R.R., & Running, S.W. (1989). Estimation of regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data. *Journal of Applied Meteorology,* Vol. 28, No 4, pp. 276-284, ISSN 1558-8424.

Oldford, S., Leblon, B., Gallant, L., & Alexander, M. (2003). Mapping pre-fire conditions in the Northwest Territories, Canada, using NOAA-AVHRR images. *Geocarto International,* Vol. 18, No 4, (December 2003), pp. 21-32, ISSN 1010-6049

Oldford, S., Leblon, B., MacLean, D., & Flannigan, M. (2006). Predicting slow drying fuel moisture codes using NOAA-AVHRR images. *International Journal of Remote Sensing,* Vol. 27, No 18, (September 2006), pp. 3881-3902, ISSN 0143-1161.

Olioso, A., Chauki, H., Courault, D., & Wigneron, J.P. (1999). Estimation of evapotranspiration and photosynthesis by assimilation of remote sensing data into SVAT models. *Remote Sensing of Environment,* Vol. 68, pp. 341-356, ISSN 0034-4257.

Paltridge, G.W., & Barber, J. (1988) Monitoring grassland dryness and fire potential in Australia with NOAA-AVHRR data. *Remote Sensing of Environment,* Vol. 25, No 3, (August 1988), pp. 381-394, ISSN 0034-4257.

Pereira, J.M.C. (1992). Burned area mapping with conventional and selective principal component analysis, *Finisterra* Vo. 27, No 53–54, pp. 63–78.

Pereira, J.M.C., Sousa, A. M. O., Sà, A. C. L., Martin, P. & Chuvieco, E. (1999). Regional-scale burnt area mapping in Southern Europe using NOAA-AVHRR 1 Km data, In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, E. Chuvieco Ed., pp. 139-155, Springer-Verlag, ISBN 978-3540657675, Berlin.

Pierce, L.L., Running, S. W., & Riggs, G.A. (1990). Remote detection of canopy water stress in coniferous forests using the NS001 Thematic Mapper Simulator and the Thermal Infrared Multispectral Scanner. *Photogrammetry Engineering and Remote Sensing,* Vol. 56, No 5, pp. 579-586.

Pinol, J., Filella, I., Ogaya, R., & Penuelas, J. (1998). Ground-based spectroradiometric estimation of live fine fuel moisture of Mediterranean plants. *Agricultural and Forest Meteorology,* Vol. 90, *No 3, (April 1998),* pp. 173-186, ISSN 0168-1923.

Prins, E. M., & Menzel, W. P. (1992). Geostationary satellite detection of biomass burning in South America, *International Journal of Remote Sensing*, Vol. 13, No 15, (October 1992), pp. 2783–2799, ISSN 0143-1161

Prins, E. M., Feltz, J. M., Menzel, W. P. & Ward, D. E. (1998). An overview of GOES-8 diurnal fire and smoke results for SCAR-B and 1995 fire season in South America, *Journal of Geophysical Research-Atmospheres*, Vol. 103, N0 D24, (December 1998), pp. 31,821– 31,835. ISSN 0148–0227

Prosper-Laget, V., Douguedroit, A., & Guinot, J.P. (1994). A satellite index of forest fire occurence risk in summer in the Mediterranean area. In *Proceedings* 2nd *International Conference on Forest Fire Research*, vol. 2, pp. 637-646, Coimbra, Portugal, November 1994.

Prosper-Laget, V., Wigneron, J.P., Guinot, J.P., & Seguin, B. (1995). Utilisation du satellite NOAA pour la détection des risques d'incendies de forêts. *La Météorologie,* Vol. 8, No 10, pp. 28-38, ISSN 0026-1181.

Roy, D., P. E. Lewis, & C. O. Justice (2002), Burned area mapping using multi-temporal moderate spatial resolution data: A bi-directional reflectance model-based expectation approach, *Remote Sensing of Environment,* Vol. 83, No 1– 2, (November 2002), pp. 263–286, ISSN 0034-4257

Roy, D., Y. Jin, P. Lewis, & C. Justice (2005), Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data, *Remote Sensing of Environment,* Vol. 97, No 2, (July 2005), pp. 137–162, ISSN 0034-4257

San-Miguel-Ayanz, J., Annoni, A., & Schmuck, G. (1998). The use of satellite imagery for retrieval of information on wildfire damage in Mediterranean landscapes. *Proceedings of ERIM'98, 27th International Symposium on Remote Sensing of Environment: Information for sustainability*, pp. 758-762, Tromsö, Norway, June, 1998.

San-Miguel-Ayanz, J., Ravail, N., Kelha, V. & Ollero, A. (2005). Active fire detection for emergency management: Potentials and limitations for the operational use of remote sensing. *Natural Hazards,* Vol. 35, No 3, (July 2005), pp. 361-376, ISSN 0921-030X.

San-Miguel-Ayanz J., Pereira, J., Boca, R., Strobl, P., Kucera, J., & Pekkarinen, A. (2009). Forest fires in the European Mediterranean region: mapping and analysis of burned areas. In *Earth Observation of Wildland Fires in Mediterranean Ecosystems*, Chuvieco Emilio (Ed.), pp. 189-204. Springer-Verlag ISBN 978-3-642-01753-7, Berlin Heidelberg.

San-Miguel-Ayanz, J., Schulte, E., Schmuck, G., Camia, A., Strobl, P., Liberta, G., Giovando, C., Boca, R., Sedano, F., Kempeneers, P., McInerney, D., Withmore, C., Santos de Oliveira, S., Rodrigues, M., Durrant, T., Corti, P., Oehler, F., Vilar L., & Amatulli, G. (2012). Comprehensive monitoring of wildfires in europe: the European Forest Fire Information System (EFFIS), in *Approaches to Managing Disaster - Assessing Hazards, Emergencies and Disaster Impacts*, John Tiefenbacher (Ed.), pp. 87-105, InTech, ISBN 978-953-51-0294-6.

Sedano, F., Kempeneers, P., Strobl, P., McInerney D., & San-Miguel-Ayanz, J. (2012). Increasing spatial detail of burned scar maps using irs-awifs data for Mediterranean Europe. *Remote Sensing*, Vol. 4, No 3, pp. 726-744, ISSN 2072-4292

Sedano, F., Kempeners, P., San-Miguel-Ayanz, J., Strobl, P., & Vogt, P. (2012). Towards a pan-European burn scar mapping methodology based on single-date medium resolution optical remote sensing data. *International Journal of Applied Earth Observation and Geoinformation*, (in press), ISSN 0303-2434.

Siegert, F. & Ruecker, G., (2000). Use of multitemporal ERS-2 SAR images for identification of burned scars in south-east Asian tropical rainforest. *International Journal of Remote Sensing*, Vol. 21, No 4, (January 2000), pp. 831-837, ISSN 0143-1161

Simon, M., S. Plummer, F. Fierens, J. J. Hoelzemann, and O. Arino (2004), Burnt area detection at global scale using ATSR-2: The GLOBSCAR products and their qualification. *Journal of Geophysical Research-Atmospheres*, Vol. 109, (July 2004), p. D14S02, ISSN 0148–0227

Strickland, G., Leblon, B., Gallant, L., & Alexander, M.E. (2001). Monitoring fire danger of northern boreal forests from optical and thermal infrared NOAA-AVHRR images. *Proceedings 23th Canadian Remote Sensing Symposium*, pp. 667-676, Ste-Foy, Canada, June 2001.

Tansey, K., Grégoire, J.M., Stroppiana, D., Sousa, A., Silva, J., Pereira, J. M. C., Boschetti, L., Maggi, M., Brivio, P. A., Flasse, S., Ershov, D., Binaghi, E., Graetz, D., & Peduzzi, P. (2004), Vegetation burning in the year 2000: Global burned area estimates from SPOT VEGETATION data, *Journal of Geophysical Research-Atmospheres*, Vol. 109, (June 2004), p. D14S03, ISSN 0148–0227.

Teillet, P.M., Dudelzak, A.E., Pultz, T.J., McNairn, H., & Chichagov, A. (2001). A framework for *in-situ* sensor measurement assimilation in remote sensing applications. *Proceedings 23th Canadian Remote Sensing Symposium*, pp. 111-118, Ste-Foy, Canada, June 2001.

US Forest Service 2012. *The Wildland Fire Assessment System*. Available from http://www.wfas.net/

Ustin, S., Roberts, D.A., Pinzon, J., Jacquemoud, S., Gardner, M., Scheer, G., Castaneda, C.M., & Palacios-Orueta, A. (1998). Estimating canopy water content of chaparral shrubs using optical methods. *Remote Sensing of Environment,* Vol. 65, No 3, (September 1998), pp. 280-291, ISSN 0034-4257.

van Zyl, J.J., Arii, M., & Kim, Y. (2011). Model-based decomposition of polarimetric sar covariance matrices constrained for nonnegative eigenvalues. *IEEE Transactions Geoscience and Remote Sensing*, Vol. 49, No 9, (September 2011), pp. 3452-3459, ISSN 0196-2892

Vidal, A., & Devaux-Ros, C. (1995) Evaluating forest fire hazard with a Landsat TM derived water stress index. *Agricultural and Forest Meteorology*, Vol. 77, *No 3–4*, (*December 1995),* pp. 207-224, ISSN 0168-1923.

Vidal, A., Pinglo, F., Durand, H., Devaux-Ros, C., & Maillet, A. (1994). Evaluation of a temporal fire risk index in Mediterranean forests from NOAA thermal IR. *Remote Sensing of Environment,* Vol. 49, No 3, (September 1994), pp. 296-303, ISSN 0034-4257.

Yebra, M., & Chuvieco, E., 2009. Linking ecological information and radiative transfer models to estimate fuel moisture content in the Mediterranean region of Spain Solving the ill-posed inverse problem. *Remote Sensing of Environment*, Vol. 113, No 11, (November 2009), pp. 2403–2411, ISSN 0034-4257.

Yebra, M., Chuvieco, E., & Riaño, D., 2008. Estimation of live Fuel Moisture Content from MODIS images for fire risk assessment. *Agricultural and Forest Meteorology,* Vol. 148, No 4, (April 2008), pp. 523–536., ISSN 0168-1923.