OBJECT-BASED VS PIXEL-BASED MAPPING OF FIRE SCARS USING MULTI-SCALE SATELLITE DATA

G. Mallinis [a], M. Pleniou[b], N. Koutsias[b, *]

[a] Department of Forestry & Management of the Environment and Natural Resources, Democritus University of Thrace, GR-68200 Orestiada, Greece- gmallin@for.auth.gr

[b] Department of Environmental and Natural Resources Management, University of Ioannina, G. Seferi 2, GR-30100 Agrinio, Greece- mpleniou@cc.uoi.gr, nkoutsia@cc.uoi.gr

KEY WORDS: Burned area, multi-scale IKONOS, ASTER, MODIS, CART

ABSTRACT:

Assessment and mapping of burned areas using satellite data has been implemented so far at local, regional and global scale, by employing various image analysis techniques, according to the spectral and spatial characteristics of the remotely sensed data. The spatial resolution of satellite data together with landscape configuration guides of the decision for the classification approach to be applied, since it determines the existence of a High- or a Low-resolution model of the scene. The recent availability of very high spatial resolution satellite data reconsiders the digital methods used for information extraction and thematic mapping. The strength of object-based analysis lies on the fact that individual pixels, composing real world objects, can be identified in the satellite imagery and classified using semantic and heuristic knowledge Object-based analysis of remotely sensed imagery has attracted attention in burned area mapping; a particular case of thematic mapping. However, some questions are posed regarding its applicability and performance at multiple scales.

In this study, we discuss the strengths and the weaknesses of the object-based classification approach and compare it with a classical pixel-based for burned area mapping in a Mediterranean study area. Multi-sensor satellite data of multiple spectral and spatial resolutions from IKONOS, ASTER and MODIS sensors of the same burned area allowed us to evaluate the multi-scale performance of the object-based approach. Large scale true color aerial photography acquired shortly after the fire served for accuracy assessment of the multi-scale burned area maps.

1. INTODUCTION

Purely natural or human-induced disasters occur in our day lives resulting to short- and long-term consequences. Although, our current technology and knowledge to prevent natural hazards is limited or in certain cases even inexistent, the disaster situation can be avoided or at least diminished by taking appropriate measurements (San Miguel-Ayanz et al., 2000). Satellite remote sensing can be used in disaster management for prevention, preparedness, relief and reconstruction, however practically it is usually used for warning and monitoring (Van Westen, 2002).

Similar to other natural disasters, such as floods, earthquakes, extreme climatic conditions, landslides, etc., three conceptual phases are recognized in wildland fires using as reference point their ignition and spread; the pre-, during, and post-fire phase. Numerous remote sensing studies can be found in literature focusing to one of these three phases. Specifically, research is focused on hazard and risk assessment (Chuvieco and Salas, 1996; Leblon et al., 2001), detection and monitoring of the fire itself (Flasse and Caetano, 1996; Justice et al., 1996; Ambrosia et al., 1998; Li et al., 2000), or detection and monitoring of burned areas (Milne, 1986; Jakubuskas et al., 1990; López-Garcia and Caselles, 1991; Kasischke et al., 1992; Chuvieco and Martin, 1994; Barbosa et al., 1998; Chuvieco et al., 1998; Stroppiana et al., 2002)

In these groups of applications, satellite data of multiple spatial, spectral, radiometric and temporal resolutions constitute the primer source of information. Their choice depends mainly on the specifications arising from the scale, purpose and objectives of the study. In burned land mapping, which this paper refers to, discrimination problems have been observed between burned surfaces and water bodies, urban areas, and shadows and between slightly burned and unburned vegetation (Chuvieco and Congalton, 1988; Arino et al., 2001; Vasconcelos et al., 2001). The diverse and complex spatial and temporal pattern of spectral responses of burned surfaces is partially responsible for inaccuracies presented in their detection and mapping (Pereira et al., 1997). Although many methods have been developed, none of them can ensure the successful detection and mapping of burned surfaces by addressing effectively all numerous problems and limitations existing. In that sense, satellite remote sensing for burned land mapping still remains an active topic of research (Pereira et al., 1997). The availability of satellite data with very fine spatial resolution brought about a reconsideration of the methods used so far for the extraction of the information. The existence of a high resolution scene model (H-resolution) (Strahler et al., 1986; Hay et al., 1996) for most of the applications motivated, among others, a shifting from adopting the pixel as unit of classification to object-based classification methods (Hay et al., 2005). New concepts of image processing, as well as algorithms for the delineation of image objects such as the Fractal Net Evolution Approach (FNEA) or the Multiscale Object-Specific Segmentation (MOSS) (Hay et al., 2003) have been evolved. Mitri and Gitas (2004) relied on the eCognition software to map burned areas in the island of Thasos using a post-fire Landsat TM image, presenting an overall accuracy around 99% compared to an 82% accuracy of a pixel-based approach. Object based burned area mapping has been also implented using NOAA AVHRR low spatial resolution imagey (Gitas et al., 2004) and IKONOS very high spatial resolution imagery (Mitri and Gitas, 2006).

Our study compares the perfomance of pixel-based and object based classification approaches for burned area mapping over sensors with different spatial, spectral and radiometric characteristics. More specifically, we used MODIS, ASTER and IKONOS images acquired shortly after a major fire event in the summer of 2007 near Athens, Greece.

2. STUDY AREA AND DATASET

2.1 Description of the study area

Mt Parnitha (or Mt Parnis), the highest of the four mountains surrounding the Attica basin, lies 30 km NW of central Athens. Parnitha is situated between 38° 05'–38°15'N and 23°31'–23°51'E, in the phytogeographical area of Sterea Ellas (Central Greece). In 1961 the entire mountain (20,000 hectares) was declared as National Park and most of human activities were prohibited in its core zone.. In addition, Mt Parnitha belongs to the 'Natura2000' Network, a network of sites hosting valuable habitats and species established by the European Union through Directive 92/43/EEC (Aplada et al., 2007).

Mt Parnitha experienced a severe damage from a wildfire outbreak on 28 June 2007, which was suppressed 5 days latter. Significant parts of the Parnitha National Park were destroyed, and in total the fire burnt 4726 ha of the core of the national forest in a few days, being thus one of the worst recorded wildfires in Attica. The fire devastated the 80% of the Greek Fir and Aleppo Pine part of the forest, and many animals of the red deer population (an endangered species), birds, and other rare species. Scientists estimate that the Greek Fir recovery time may be as long as a century, as it is a mountainous species not adapted to fires (Kontoes et al., 2009).

2.2 Dataset

A very high spatial resolution IKONOS image was acquired on July 8th 2007. The multispectral sensor of the satellite produce images with 3 bands (1-3) covering the visible and one band (band 4) covering the near-infrared part of the spectrum while the spatial resolution is 4 meters.

Also, a medium-high spatial resolution ASTER image, obtained on July 20th 2007 was employed in our study. It collects data in the visible/near infrared (bands1 to 3), short wave infrared (bands 4-9), and thermal infrared bands (bands 10-14). Among the 14 ASTER bands we only considered the three channels in the VNIR region and six channels in the SWIR region, while the TIR channels were excluded.

The MODIS image was obtained on September 2007. MODIS imagery has 36 spectral bands and spectral bands 1-7 are closely related to land cover mapping. In this study, a multispectral MODIS image with bands 1-7 is used: Spectral band 1 (red), band 2 (near-infrared), band 3 (blue), band 4 (green), and bands 5-7 (mid-infrared). Bands 1 and 2 have spatial resolution of 250m and bands 3-7 have spatial resolution of 500 m.

Furthermore, natural colour, large scale aerial photography acquired immediately after the fire from Hellenic Military Geographical Service was orthorectified using photogrammetric procedures and used as part of the evaluation procedures.

3. METHODS

3.1 Data preprocessing

All satellite images were geometrically corrected using ground control points extracted from orthophotos a 1:5.000 scale and a 10 metre digital elevation model (DEM). Also, a dark object subtraction approach was applied to correct the effects caused by the solar zenith angle, solar radiance and atmospheric scattering (Chavez Jr, 1996).

Also, the SWIR component of the ASTER imagery was resampled to 15 meters to match the spatial resolution of the VNIR component while bands 1-2 of the MODIS image were resampled to a 500 meters resolution. We did not considered the use of additional synthetic channnels generated from spectral and spatial enhancement of the original imagery since it would complicate the discussion of the results.

3.2 Object- based analysis

The segmentation algorithm applied in our work is a component of the multi-scale object-oriented FNEA concept (Benz et al., 2004). Through this segmentation technique, embedded within the commercial software Definiens Professional, individual pixels are perceived as the initial regions which are sequentially merged pairwise into larger ones with the intent of minimizing the heterogeneity of the resulting objects. The sequence of the merging objects, as well the size and shape of the resulting objects, are empirically determined by the user (Mallinis et al., 2008). The segmentation of the image data at fine and coarse scales is important in the object-based multiscale analysis, in order to extract boundaries of the dominant objects occurring at the corresponding scales (Hall et al., 2004).

The resulting objects can then be described and classified by an extensive variety of their features related to the color, texture, form, and horizontal and vertical context properties. Available classification approaches in the Definiens software include the use the NN classifier and the introduction of individual membership functions. In our study, a Classification And Regression Tree Analysis (CART) was adopted to select the most appropriate features and to define the thresholds for the discrimination of the different burn severity levels (Mallinis et al., 2008). Through this analysis, the most appropriate explanatory variables can be selected to predict certain response values. The results of this sequential approach are usually presented in a tree-form that is called classification tree when the predicted value is categorical or regression tree when the dependent variable is continuous (Mallinis et al., 2009).

3.3 Pixel-based analysis

The familiar parametric Maximum Likelihood (ML) algorithm was used to implement the pixel based approach. Pure spectral pixels corresponding to burned, vigorous vegetation, barren and shadow ground areas were identified in each of the three images.

3.4 Comparative evaluation of the techniques

The Kappa coefficient of agreement and overall accuracies estimated using reference data generated by the orthorectified aerial imagery, was used to compare the two approaches (Chuvieco and Congalton, 1989). Also, a pairwise test statistic Z was also applied on the Kappa coefficient of agreement to statistically compare the results of the two classification schemes:

$$Z = |K_1 - K_2| / \sqrt{\mathrm{var}K_1 - \mathrm{var}K_2} \qquad (1)$$

4. RESULTS AND DISCUSSION

For the IKONOS and ASTER images a top-down approach was followed for the segmentation process as well as for the development of the multiscale hierarchy. This implies the generation of the upper levels of the hierarchy composed from coarser objects. In the case of the MODIS image, due to the low spatial resolution, a level was generated through multiresolution segmnentation, while in a second step, an upper level was derived through classification based on fusion of the classifed objects in the first level.

Level	Scale factor	Bands	Weight	Heterogeneity	
				Spectral	Spatial
4	100	4/3/2	1/0.8/0.6	0.9	0.1
3	60	4/3/2	1/0.8/0.6	0.9	0.1
2	15	4/3/2	1/0.8/0.6	0.9	0.1
1	5	4	1/0.8/0.6	0.7	0.3

Table 1. Parameters used for the segmentation of the IKONOS image

Level	Scale factor	Bands	Weight	Heterogeneity	
				Spectral	Spatial
3	80	9/4/3/1	1/1/1	0.9	0.1
2	20	9/4/3/1	1/1/1	0.9	0.1
1	5	9/4/3/1	1/1/1	0.7	0.3

Table 2. Parameters used for the segmentation of the ASTER image

Level	Scale factor	Bands	Weight	Heterogeneity	
				Spectral	Spatial
1	3	7/4/2	1/1/1	1	-
2	Classification-based fusion				

Table 3. Parameters used for the segmentation of the MODIS image

The layers used for the segmentation of the images (Tables 1 to 3) were chosen empirically based on visual inspection of the results as well as separability analysis of the main land cover categories using the Jefferies-Matusita index in the case of the higher spectral resolution ASTER and MODIS images.

For the classification of the IKONOS image (Table 4), the information content of the NIR band was used for all cases of burned objects. Also, in the three lower levels of the hierarchy, class-related information from the corresponding upper level was used.

Respectively, for the classification of the ASTER image (Table 5), features corresponding to the SWIR part of the spectrum were primary used. None of the bands belonging to the visible part of the spectrum (bands 1 and 2) were selected.

Finally, the classification of the MODIS image was based on the use of information of the NIR (band 2) and SWIR (band 7) part of the spectrum, while the final classification of the second (upper) level objects, relied on class-related information of the sub-objects.

In general, the results of the feature selection process are in accordance with the findings of other studies considering the spectral behavior of the burned areas.

Level	Class name	Features
4	Possibly Burned (PB)	Mean(Ik4), Brighness
3	Totally Burned (TB)	Mean(Ik4), Ratio(Ik3), Existence of super-objects(PB)
	Burned-Vegetation (BV)	Mean(Ik4), Ratio (Ik3), Ratio(Ik1), Existence of super-objects (PB)
	Burned-Vegetation-Ground (BVG)	Mean(Ik4), Min(Ik2), Existence of super-objects (PB)
2	Burned at 2	Mean(Ik4), Mean(Ik4/Ik3), Existence of super-objects(BV or BVG)
	Semi Burned (SB)	Mean (Ik4/Ik3), Existence of super-objects(BV or BVG)
1	Burned at 1	Max diff, Existence of super-objects(SB)

Table 4. Classification scheme and features used for the classification of the IKONOS image

The most informtative region of the spectrum is the SWIR, followed by the NIR whilst in the visible part, the green radiation is the most useful (Koutsias and Karteris, 2000). In the visible part of electromagnetic spectrum, the spectral signal of burned surfaces is quite similar to the spectral signal of unaffected vegetation. Nevertheless different studies carried out in the visible area (0.4-0.7 μm) indicate a multi-spectral behavior of burned areas depending on the type of the affected vegetation, severity of burning, etc. (Pereira et al., 1997; Arino et al., 2001). On the other hand, a strong increase in reflectance of the affected areas is typically observed in the mid-infrared region. Removal of the vegetation layer and replacement with charcoal reduces the canopy moisture and canopy shadow, which absorbs the radiation in this spectral region. As a consequence, burned areas are expected to have higher reflectance than those of a healthy vegetation (Koutsias and Karteris, 1998; Van Wagtendonk et al., 2004).

Level	Class name	Features
3	Possibly Burned (PB)	Min(ASTER9), Min(ASTER3)
2	Totally Burned (TB)	Min(ASTER9), Ratio(ASTER7), Existence of super-objects(PB)
	Medium Burned (MB)	Min(ASTER9), Ratio(ASTER9), Ratio (ASTER7), Existence of super-objects(PB)
	Low Burned (LB)	Min(ASTER3), Ratio(ASTER7), Ratio (ASTER1), Existence of super-objects(PB)
1	Burned at 1	Ratio(ASTER3), Ratio(ASTER4), Existence of super-objects(MB or LB)

Table 5. Classification scheme and features used for the classification of the ASTER image

Level	Class name	Features
1	Possibly Burned (PB)	Min (Modis2), Min (Modis7)
2	Burned at 1	Min(Modis2), Existence of sub-objects(PB)

Table 6. Classification scheme and features used for the classification of the MODIS image

In the case of the Pixel Based Image Analysis (PBIA) approach, we considered all bands in the classification processs.

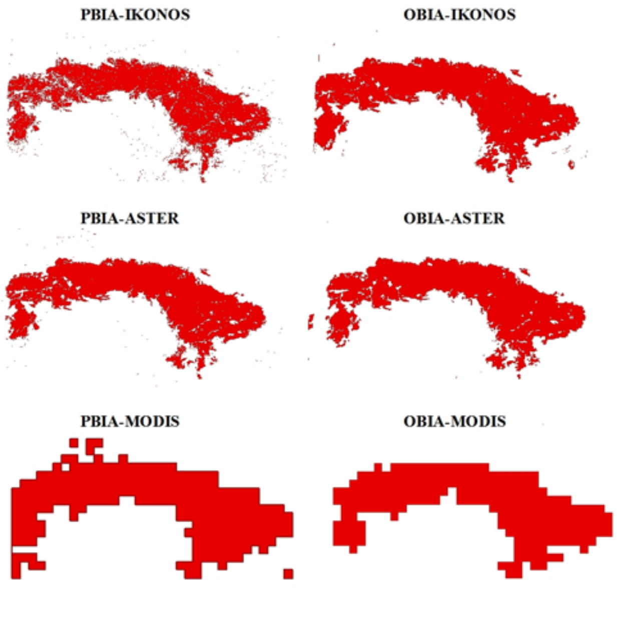

Figure 1. Burned area maps following the pixel-based and the object-based approaches

The classification assesment procedure indicated that higher accuracies were achieved with the use of the IKONOS imagery. OBIA slightly outperforms the PBIA approach; however, the Z-statistic calculated indicated that these are non-significant.

Method	Overall accuracy (%)	Khat	Z-statistic
	IKONOS		
			OBIA
OBIA	94.86	0.89	
PBIA	94.36	0.88	0.499
	ASTER		
Method	Overall accuracy (%)	Khat	Z-statistic
			OBIA
OBIA	93.99	0.87	
PBIA	95.24	0.9	0.444
	MODIS		
Method	Overall accuracy (%)	Khat	Z-statistic
			OBIA
OBIA	85.48	0.7	
PBIA	84.98	0.69	0.155

Table 7. Overall accuracy and Khat values obtained based on the reference points. In addition, evaluation of the classification approaches based on the Z statistic pairwise comparison of the Khat values.

The accuracies obtained from the 15 meters ASTER image are surprisingly high, since the pixel-based classification of the ASTER image returned the highest accuracy (95.24%). Object based classification of the ASTER image was found also to be high (93.99%), but again the difference between the two approaches was found to be not statistically signifficant.

The OBIA classification of the MODIS image was slightly better than the PBIA classification (85.48% and 84.98% respectively). Accordingly to these figures, this difference was found to be non-significant.

5. CONCLUSIONS

In the present study we explored the relative perfomance of object based and pixel based analysis over a burned area in Greece. We assessed the accuracy obtained on a multiple scale basis, considering satellite data with very high, medium/high and low spatial resolution. Interestingly, at none of these scales, we found a statistical significant difference between the two approaches. Also, the IKONOS and ASTER imagery produced burned area maps with comparable accuracy. Further issues, such as the spectral information content and the complexity of the scene will be adressed in the future, as factors affecting the relative merits of adopting the object versus the pixel as the primary unit of the analysis, in the case of burned area mapping

Acknowledgements

Part of the research has been supported by FUME project “Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world” Grant agreement no.: 243888. 7th FRAMEWORK PROGRAMME EU. MODIS data have been provided by The Land Processes Distributed Active Archive Center for MODIS data https://lpdaac.usgs.gov/lpdaac/get_data/data_pool

References

Ambrosia, V.G., Buechel, S.W., Brass, J.A., Peterson, J.R., Davies, R.H., Kane, R.J. and Spain, S., 1998. An integration of remote sensing, GIS and information distribution for wildfire detection and management. Photogramm. Eng. Remote Sens., 64:977-985.

Aplada, E., Georgiadis, T., Tiniakou, A. and Theocharopoulos, M., 2007. Phytogeography and ecological evaluation of the flora and vegetation of Mt Parnitha (Attica, Greece). Edinburgh Journal of Botany, 64:185-207.

Arino, O., Piccolini, I., Kasischke, E., Siegert, F., Chuvieco, E., Martin, P., Li, Z., Fraser, R., Eva, H., Stroppiana, D., Pereira, J., Silva, J.M.N., Roy, D. and Barbosa, P.M., 2001. Methods of mapping burned surfaces in vegetation fires. In: F.J. Ahern, J.G. Goldammer and C.O. Justice (Editor), Global and Regional Vegetation Fire Monitoring from Space: Planning a Coordinated International Effort. SPB, Academic Publishing, The Hague, The Netherlands, pp. 227-255.

Barbosa, P.M., Pereira, J.M.C. and Gregoire, J.-M., 1998. Compositing criteria for burned area assessment using multitemporal low resolution satellite data. Remote Sens. Environ., 65:38-49.

Benz, U.C., Hofmann, P., Willhauck, G., Lingenfelder, I. and Heynen, M., 2004. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. ISPRS Journal of Photogrammetry and Remote Sensing, 58:239-258.

Chavez Jr, P.S., 1996. Image-based atmospheric corrections - Revisited and improved. Photogrammetric Engineering and Remote Sensing, 62:1025-1036.

Chuvieco, E. and Congalton, R.G., 1988. Mapping and inventory of forest fires from digital processing of TM data. Geocarto Int., 4:41-53.

Chuvieco, E. and Congalton, R.G., 1989. Application of remote sensing and geographic information systems to forest fire hazard mapping. Remote Sensing of Environment, 29:147-159.

Chuvieco, E. and Martin, M.P., 1994. A simple method for fire growth mapping using AVHRR channel 3 data. Int. J. Remote Sens.

Chuvieco, E. and Salas, J., 1996. Mapping the spatial distribution of forest fire danger using GIS. Int. J. Geogr. Inf. Syst., 10:333-345.

Chuvieco, E., Salas, J., Barredo, J.I., Carvacho, L., Karteris, M. and Koutsias, N., 1998. Global patterns of large fires occurrence in the European Mediterranean Basin: A G.I.S. analysis. In: D.X. Viegas (Editor), III International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology. ADAI, University of Coimbra, Luso, Portugal, pp. 2447-2462.

Flasse, S.P. and Caetano, P., 1996. A contextual algorith for AVHRR fire detection. Int. J. Remote Sens., 17:419-424.

Gitas, I.Z., Mitri, G.H. and Ventura, G., 2004. Object-based image classification for burned area mapping of Creus Cape, Spain, using NOAA-AVHRR imagery. Remote Sensing of Environment, 92:409-413.

Hall, O., Hay, G.J., Bouchard, A. and Marceau, D.J., 2004. Detecting dominant landscape objects through multiple scales: An integration of object-specific methods and watershed segmentation. Landscape Ecology, 19:59-76.

Hay, G.J., Blaschke, T., Marceau, D.J. and Bouchard, A., 2003. A comparison of three image-object methods for the multiscale analysis of landscape structure. ISPRS Journal of Photogrammetry and Remote Sensing, 57:327-345.

Hay, G.J., Castilla, G., Wulder, M.A. and Ruiz, J.R., 2005. An automated object-based approach for the multiscale image segmentation of forest scenes. International Journal of Applied Earth Observation and Geoinformation, 7:339-359.

Hay, G.J., Niemann, K.O. and McLean, G.F., 1996. An object-specific image-texture analysis of H-resolution forest imagery. Remote Sensing of Environment, 55:108-122.

Jakubuskas, M.E., Lulla, K.P. and Mausel, P.W., 1990. Assessment of vegetation change in a fire-altered forest landscape. Photogramm. Eng. Remote Sens., 56:371-377.

Justice, C.O., Kendall, J.D., Dowty, P.R. and Scholes, R.J., 1996. Satellite remote sensing of fires during the SAFARI campaign using NOAA Advanced Very High Resolution Radiometer. J. Geophys. Res.-Atmos., 101:23851-23863.

Kasischke, E.S., Bourgeau-Chavez, L.L., French, N.H.F., Harrell, P. and Christensen, N.L., Jr., 1992. Initial observations on using SAR to monitor wildfires scars in boreal forests. Int. J. Remote Sens., 13:3495-3501.

Kontoes, C.C., Poilvé, H., Florsch, G., Keramitsoglou, I. and Paralikidis, S., 2009. A comparative analysis of a fixed thresholding vs. a classification tree approach for operational burn scar detection and mapping. International Journal of Applied Earth Observation and Geoinformation, 11:299-316.

Koutsias, N. and Karteris, M., 1998. Logistic regression modelling of multitemporal Thematic Mapper data for burned area mapping. International Journal of Remote Sensing, 19:3499-3515.

Koutsias, N. and Karteris, M., 2000. Burned area mapping using logistic regression modeling of a single post-fire Landsat-5 Thematic Mapper image. International Journal of Remote Sensing, 21:673-687.

Leblon, B., Alexander, M., Chen, J. and White, S., 2001. Monitoring fire danger of northern boreal forests with NOAA-AVHRR NDVI images. Int. J. Remote Sens., 22:2839-2846.

Li, Z., Nadon, S., Cihlar, J. and Stocks, B., 2000. Satellite-based mapping of Canadian boreal forest fires: evaluation and comparison of algorithms. Int. J. Remote Sens., 21:3071-3082.

López-Garcia, M.J. and Caselles, V., 1991. Mapping burns and natural reforestation using Thematic Mapper data. Geocarto Int., 1:31-37.

Mallinis, G., Koutsias, N., Tsakiri-Strati, M. and Karteris, M., 2008. Object-based classification using Quickbird imagery for delineating forest vegetation polygons in a Mediterranean test site. ISPRS Journal of Photogrammetry and Remote Sensing, 63:237-250.

Mallinis, G., Maris, F., Kalinderis, I. and Koutsias, N., 2009. Assessment of post-fire soil erosion risk in fire-affected watersheds using remote sensing and GIS. GIScience and Remote Sensing, 46:388-410.

Milne, A.K., 1986. The use of remote sensing in mapping and monitoring vegetational change associated with bushfire events in eastern Australia. Geocarto Int., 1:25-32.

Mitri, G.H. and Gitas, I.Z., 2004. A semi-automated object-oriented model for burned area mapping in the Mediterranean region using Landsat-TM imagery. International Journal of Wildland Fire, 13:367-376.

Mitri, G.H. and Gitas, I.Z., 2006. Fire type mapping using object-based classification of Ikonos imagery. International Journal of Wildland Fire, 15:457-462.

Pereira, J.M.C., Chuvieco, E., Beaudoin, A. and Desbois, N., 1997. Remote sensing of burned areas: A review. In: E. Chuvieco (Editor), A review of remote sensing methods for the study of large wildland fires. Universidad de Alcala, Alcala de Henares, Spain, pp. 127-183.

San Miguel-Ayanz, J., Vogt, J., De Roo, A. and Schmuck, G., 2000. Natural hazards monitoring: forest fires, droughts and floods - the example of European pilot projects. Surv. Geophys., 21:291-305.

Strahler, A.H., Woodcock, C.E. and Smith, J.A., 1986. On the nature of models in remote sensing. Remote Sensing of Environment, 20:121-139.

Stroppiana, D., Pinnock, S., Pereira, J.M.C. and Gregoire, J.-M., 2002. Radiometric analysis of SPOT-VEGETATION images for burnt area detection in Northern Australia. Remote Sens. Environ., 82:21-37.

Van Wagtendonk, J.W., Root, R.R. and Key, C.H., 2004. Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity. Remote Sensing of Environment, 92:397-408.

Van Westen, C.J., 2002. Remote sensing and geographic information systems for natural disaster management. In: A. Skidmore (Editor), Environmental Modelling with GIS and Remote Sensing. Taylor & Francis, London, pp. 200-226.

Vasconcelos, M.J.P., Silva, S., Tome, M., Alnim, M. and Pereira, J.M.C., 2001. Spatial prediction of fire ignition probabilities: comparing logistic regression and neural networks. Photogramm. Eng. Remote Sens., 67:73-81.