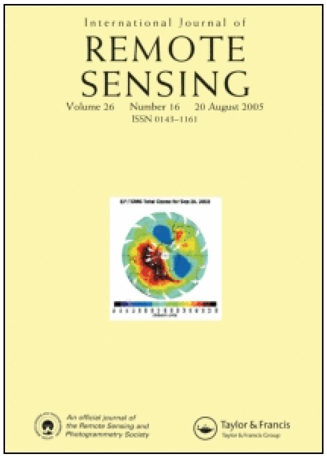

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MERIS Full Resolution data for mapping level-of-damage caused by forest fires: the Valencia de Alcántara event in August 2003

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This paper concerns an estimation of burned area and fire severity levels in the area affected by the Valencia de Alcántara forest fire, an event that took place near the border between Portugal and Spain in August 2003. 'Level-of-damage' and 'fire severity' are both defined as the impact of fire on the vegetation. The study presented herein uses satellite information from Envisat-MERIS (Medium Resolution Imaging Spectrometer) and SPOT5-HRG (Système pour l'observation de la Terre – High Resolution Geometric instrument), ground data and ancillary maps. The methodology consisted of applying linear unmixing algorithms on a post-fire MERIS image, using a post-fire SPOT5-HRG image and ground data for endmember definition. Satellite-derived level-of-damage information is used for affected area estimation and for comparison with fire severity ground measurements. Satellite-derived level-of-damage is also compared with information from the Spanish National Forest Map (NFM) to assess to what extent fire severity is related to particular forest types. Results reached so far reveal that MERIS estimations on wildfire damage over forested areas may help in establishing degrees of affection, which is useful to plan forest restoration works.

1. Introduction

Wildfires are considered a major environmental and security problem in many parts of the world, including the Mediterranean Basin where summer 2003 was especially dramatic. Wildfires play a critical role in many aspects of ecosystem functioning, such as biodiversity and hydrology. They may also cause the destruction of large parts of the landscape as well as the release of considerable amounts of the main greenhouse gas carbon dioxide, thereby affecting the global atmospheric chemistry and the global climate of our planet. Forest fires occurred in Portugal and Spain during 2003, and included a number of exceptionally large and uncontrolled fires, affecting more than 570 000 hectares (European Commission 2004).

It is a fact that large forest fires have spread at an unprecedented rate in Southern Europe during the last decades (Pausas and Vallejo 1999) due to changes in traditional land use patterns that have led to an unusual accumulation of forest fuels, notably increasing fire risk and fire severity (Chuvieco 1999). González-Alonso *et al.* (2004a) confirmed that during the 1987–2001 the tendency in Spain has been 'towards an increase of the vegetation activity' and consequently towards an increase of the amount of fuel.

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The use of traditional methods to map forest fires is expensive and time-consuming. Remote sensing observations have significant advantages over conventional fire mapping and fire severity assessment as demonstrated by many authors (Caetano *et al.* 1994, Navarro *et al.* 2001, Díaz-Delgado *et al.* 2003, Chafer *et al.* 2004, Key and Benson 2004). In this work, 'level-of-damage' and 'fire severity' are both defined as the impact of fire on the vegetation, which can be estimated by the amount of vegetation surviving after the fire (Ryan and Noste 1983). Most medium and large-sized forest fires produce a wide range of fire severity levels.

Fire severity has been widely related to satellite sensor response (Caetano *et al.* 1994, Navarro *et al*. 1998, Navarro *et al.* 2001, Miller and Renschler 2003, Chafer *et al.* 2004, González-Alonso *et al*. 2004b, Key and Benson 2004, Ruiz Gallardo *et al*. 2004, Van Wagtendonk *et al*. 2004, Parra and Chuvieco 2005, Walz *et al*. 2005), but reliable accuracy has yet to be gained using standard methods over different fire-size and vegetation types (Rogan 2005). The range of methods dealing with level-of-damage mapping using post-fire satellite data includes, among others (Koutsias *et al*. 1999): (i) thresholding of single bands or vegetation indices, (ii) supervised classification of original bands or vegetation indices, (iii) unsupervised classification, (iv) multivariate analysis of original bands, (v) spectral unmixing, (vi) time-series analysis, etc. Image processing for damage intensity assessment is possible thanks to the 'feasibility of remotely sensed post-fire signals generated by the effects of fire: vegetation loss, surface charring, heating and drying' (Pereira *et al*. 1999).

In the present study, it was decided to employ only post-fire images as it is considered of great interest to find a quick and affordable methodology for obtaining fire severity maps avoiding the use of pre-fire images. In doing this, money and time would be saved in terms of obtaining, correcting and normalising images. Besides, these maps could be combined with slope and soil type maps, in order to locate priority intervention areas and plan forest restoration works. Among the different techniques used to estimate burned area by means of satellite images, a variation of the linear spectral unmixing, called matched filtering, has been chosen to develop the current research.

Shimabukuro *et al.* (1994) highlighted the spectral unmixing method to solve some of the limitations relating to the differentiating of two images from affected areas, acquired before, and after, the fire. This technique aims at estimating the surface abundance of a number of pure spectral components (or 'endmembers'), together causing the observed mixed spectral signature of the pixel. The spectral unmixing technique was successfully applied by Caetano *et al*. (1994) to distinguish between burned areas, slightly burned areas and areas with a high risk of erosion. Cochrane and Souza (1998) applied this method to a Landsat-TM (Thematic Mapper) post-fire image in order to identify burned forests and quantify the level-of-damage. The matched filtering technique (Boardman *et al.* 1995) is a simplified version of the linear spectral unmixing method, where only one 'endmember' is considered. As only post-fire images are used in the present work and provided that linear spectral unmixing has been successfully applied for fire severity mapping, matched filtering seems a suitable technique.

The European Space Agency (ESA) launched the Envisat mission in March 2002, a powerful means of monitoring the state of the Earth. The Envisat satellite provides both optical and radar measurements of the Earth's surface thanks to its ten highly sophisticated instruments. One of these is the Medium Resolution Imaging Spectrometer, better known as 'MERIS'. The MERIS instrument has shown itself to be an accurate way of estimating the degree of damage caused by wildfires as a result of its multi-spectral imaging capabilities in the visible and near-infrared regions of the spectrum and its narrow spectral bands (González-Alonso *et al.* 2004b). MERIS imagery has also been used for estimating the areas affected by large fires by using to its improved spatial resolution (300m in the Full Resolution Mode) compared with other sensors, such as the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic & Atmospheric Administration (NOAA) satellite series.

The main objective of this study was to investigate and demonstrate the capability of Envisat -MERIS images to map forest fires and forest fire level-of-damage by exploiting its combination of medium spatial resolution and spectral characteristics. In fact, this work may be considered as pioneering in the use of MERIS images for fire severity mapping. Another objective was to try to find a relationship between satellite-derived level-of-damage information and ground fire severity measurements. The reliability of MERIS-derived products is assessed through the use of SPOT5-HRG data (900 times finer spatial resolution) and post-fire ground data. In doing so, the study presented herein uses satellite information from Envisat-MERIS and SPOT5-HRG (Système pour l'observation de la Terre – High Resolution Geometric instrument), ground data and ancillary maps (topographic and forest maps).

2. Material

The forest fire occurred at the study area (known as Valencia de Alcántara) affected both Spanish and Portuguese territories. It started on the 1 August 2003 and lasted for 5 days. According to Forest Authorities, it was a lightning-induced fire. The study area extends 35 by 40km and it is centred at $39^{\circ} 22'$ N latitude and $7^{\circ} 13'$ W longitude. It is a rural zone with a Mediterranean climate and vegetation dominated by pines (*Pinus pinaster*) at high densities, sessile oaks (*Quercus pyrenaica*), holm oaks (*Q. ilex*), cork trees (*Q. suber*) and chestnuts (*Castanea sativa*) at medium to low densities and scattered agrarian lands. The distribution of different forest types is also driven by particular geological and topographic characteristics. All these circumstances clearly affected the spatial pattern of the area affected by the fire.

The material used for the present work falls into four main categories: (i) satellite images and associated information, (ii) post-fire ground data, (iii) forest maps and (iv) topographic maps. Data came from different sources and were characterised by different levels of accuracy. When necessary, data were re-projected into UTM-30N-WGS84 co-ordinate system. Software used for processing and analysing data involved digital image processing packages (BEAM 2.2, ENVI 4.1, ERDAS Imagine 8.7), Geographical Information Systems (GIS) (ArcView 3.2, ArcGIS 8.3) and statistical software (Statgraphics v 5.2, SPSS V13.0.1).

Used remotely sensed data consisted of one post-fire full resolution (FR) Level-1 MERIS image (dated 8 August 2003) provided by ESA and one post-fire SPOT5-HRG image (dated 21 August 2003). MERIS images have 15 spectral bands in the visible and near-infrared (NIR) and 300 m spatial resolution in the FR mode. SPOT5-HRG images have two visible channels, plus one NIR and one short-wave infrared (SWIR) channel, all at 10m spatial resolution.

Post-fire ground data came from a field trip carried out during the first growing season after the fire (June 2004). During this survey, clearing-up work could be seen in the ravaged areas, as well as evident signs of vegetation recovery in some plots.

Information on forest species and their distribution came from the Spanish National Forest Map (NFM, 1:50 000 scale). This map contains information about forested land-cover classes and particularly about forest types, trees, bushes and pasture species and non-biotic characteristics.

Topographic maps were at 1 : 10 000 scale in the case of Spain and at 1 : 25 000 in the case of Portugal. This information was used for digital elevation model derivation, ground control points location and for navigation during the field trip. Spanish maps came from the National Geographic Institute (Instituto Geográfico Nacional) while Portuguese maps came from the Army Geographic Institute (Instituto Geográfico do Exército).

3. Methods

3.1 *Post-fire field survey*

A rapid field assessment was undertaken in order to ascertain damage and assess areas that had been burned to a variable degree, as shown in figure 1. Routes along vehicular tracks were designed all over the affected area, trying to go through every forest type and covering different degrees of fire-affection. Sample sites were located along the routes by walking 100–200 m perpendicular to the track, within areas homogenously damaged by fire. Using this methodology, a total of 85 ground plots (20m radius) were sampled during June 2004, although only 74 were finally involved in the performed analysis. The sampling process consisted on taking at least one picture of the area, a GPS record of the plot centre (averaged from several measurements) and a visual estimation of the level-of-damage (averaged from team members' assessments) according to the protocol summarised below. All this information was linked together and introduced into a GIS for further analysis.

The degree of damage caused to vegetation by a wildfire is complex to evaluate and can be affected by a high degree of subjectivity, which makes it necessary to define and characterise the different fire severity levels very precisely in order to obtain comparable measurements and avoid confusion during the process. In the present work, three levels of fire severity were established: low, moderate and high, as well as an unburned class. These three levels are considered suitable for forest management purposes, and they are also adequate for mapping fire severity by

Figure 1. A part of the Valencia de Alcántara landscape, with different types of trees having been affected by fire to different degrees.

means of remote sensing data (Navarro *et al*. 1998, Key and Benson 2004, Ruiz Gallardo *et al*. 2004, Rogan 2005, Walz *et al*. 2005).

A visual classification of fire severity, which had already been adapted to Mediterranean vegetation characteristics by Ruiz Gallardo *et al.* (2004), was chosen for the field assessment. This classification was found suitable according to the objectives of the work, as it is based in evaluating the damage caused by a fire to the vegetation cover, and does not require an extensive field campaign. The different fire severity classes are defined as follows (Ruiz Gallardo *et al.* 2004):

(1) unburned: effects of fire on vegetation cannot be observed.
(2) low: less than 50% of vegetation cover affected. Ground fuel and low shrubs are the most affected. Less than 30% of trees appear completely burned. Some of the affected trees have only been scorched in the bottom part of their stems and crowns. Unburned spots can be found.
(3) moderate: between 50 and 90% of vegetation cover affected. Ground fuels and the branches of shrubs completely consumed, even though some of them may retain the capacity to sprout. Less than 75% of trees completely burned. Most of smaller trees dead, dominant trees less affected although their crowns can be scorched up to 60%.
(4) high: more than 90% of vegetation cover completely burned and apparently dead, even though some plants may still be able to sprout. Many stems of shrubs consumed by fire, with only the lower stems remaining.

3.2 *Image pre-processing*

Geometric and radiometric corrections were performed on the satellite images in order to prepare them for further processing. The MERIS Level-1 image was first transformed into a Level-2 product using BEAM v.2.2 software which performed geometric and atmospheric corrections to produce reflectance values. The Envisat-MERIS scene was then divided into subsets in order to keep only the study area.

The SPOT5-HRG image was ortho-rectified using orbital data, a digital elevation model (DEM, 10m pixel size) and ground control points. The DEM was derived from contour lines available from a series of 1 : 10 000 and 1 : 25 000 topographic maps. The latter were also used for the location of ground control points. The ortho-rectification process was carried out using the ERDAS Imagine OrthoBASE package. The SPOT5-HRG scene was then divided into subsets in order to keep the study area. Figure 2 shows the MERIS scene and the SPOT5-HRG sub-scene.

3.3 *Level-of-damage assessment*

The technique applied in order to analyse fire severity from the available images was the matched filtering method, a simplified version of the linear spectral unmixing technique. Spectral unmixing (Smith *et al.* 1985, Settle and Drake 1993) aims at estimating the surface abundance of a number of pure spectral components (known as 'endmembers'), together causing the observed mixed spectral signature of the pixel. A linear combination of spectral 'endmembers' is chosen to decompose the mixed reflectance spectrum of each pixel into fractions of its 'endmembers' (Van Der Meer and De Jong 2000). Therefore, endmembers must be exemplified by 'pure' training classes (Caetano *et al.* 1994). The matched filtering method maximises the response of the known endmember (high-damaged vegetation in this work) and

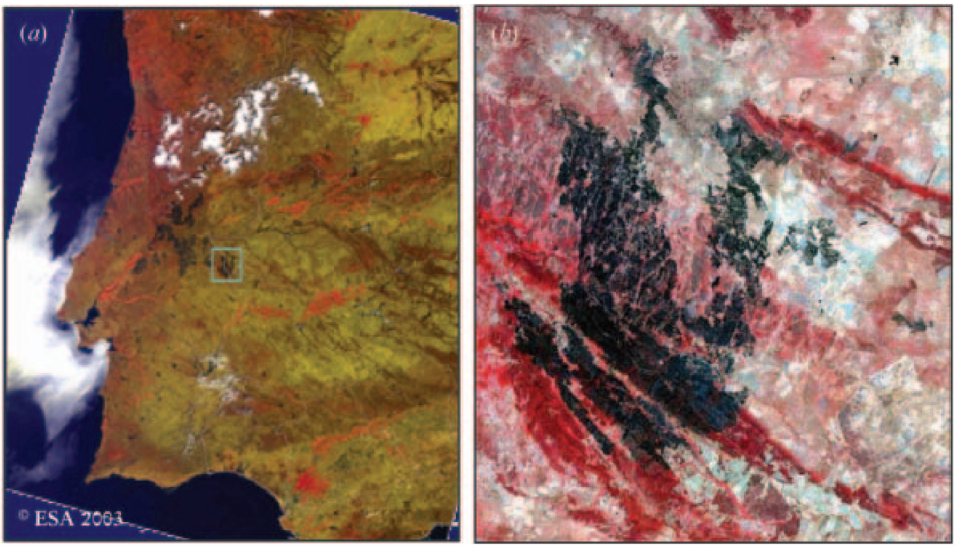

Figure 2. The fire-scarred landscape of Central Portugal and Spain, as seen by *(a)* Envisat - MERIS on 8 August 2003, with the Valencia de Alcántara fire (study area) outlined in light blue (MERIS instrument RGB image: 12,9,1 false colour composite) and *(b)* SPOT5-HRG sub-scene on 21 August 2003 (SPOT5-HRG instrument RGB image: 1,2,3 false colour composite).

suppresses the response of the rest of land-cover classes (Vázquez *et al.* 2001). The resulting image provides a means of estimating relative abundance of 'high-damaged' vegetation, and therefore provides an assessment of fire severity.

Both MERIS and SPOT5-HRG images were processed using the matched filtering algorithm implemented on ENVI. The delimitation of regions of interest containing 'pure' high-damaged pixels was carried out on the SPOT5-HRG post-fire image, using information from the post-fire field survey (ground data) and from the NFM. The idea was to draw regions in places where, according to the different sources of information (image itself, pictures and field level-of-damage assessment) the area was highly damaged by fire. The NFM was used to assure that burned spectral data came from all the available forest-type classes. The set of regions of interest defined on the SPOT5-HRG image was used for the matched filtering classification process on both Envisat-MERIS and SPOT5-HRG images.

4. Results and Discussion

4.1 *Level-of-damage from MERIS and SPOT5-HRG data*

Applying ENVI matched filtering algorithm on the whole set of single bands in each case, two new likelihood images were produced. This method assigns a probability value to any single pixel in the original scene, generating a new image in which the histogram is typically bimodal provided that a stretched window is set around the fire-scar (the extension of the study area is shown in figure 2(*b*) and described in section 2). Such histograms have one peak corresponding to burned pixels and another one corresponding to the background, i.e. non-burned areas. Figure 3 shows histograms resulting from processing both MERIS and SPOT5-HRG sub-scenes. The resulting probability values have to be thresholded in order to remove

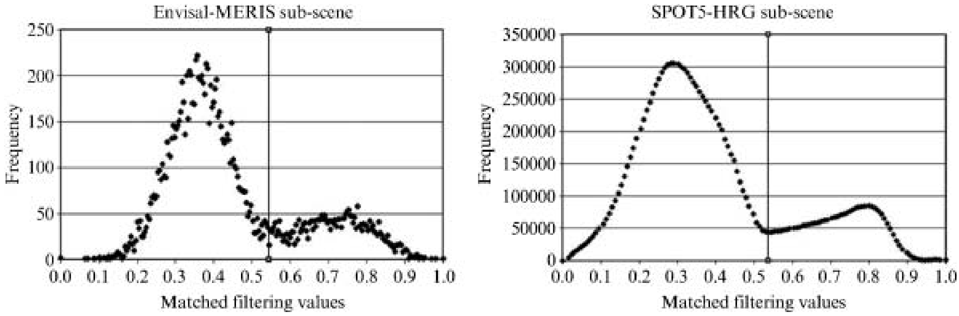

Figure 3. Histograms resulting from applying the matched filtering technique to Envisat-MERIS and SPOT5-HRG sub-scenes (study area). Relative minimum values separating 'unburned' and 'burned' pixels are shown.

background values (unburned pixels) and produce a fire severity map. This thresholding process consisted of two steps: (i) looking for the relative minimum value within the histogram of the 'matched filtered' images (shown in figure 3), and (ii) using this value to remove those pixels that can be classified as 'unburned'. This minimum value resulted 0.5351 in the case of Envisat-MERIS and 0.5368 in the case of SPOT5-HRG. The resulting satellite-derived level-of-damage images have continuous values between their corresponding minimum value and 1.0 as shown in figures 3 and 4. For comparison purposes, the latter were also reclassified into categorical variables as explained in section 4.2.

Results reached so far allowed an evaluation of fire-affected area and a comparison between sensors. Table 1 presents some figures that are worth pointing out. Coarser spatial resolution data tended to overestimate the area damaged by fire but in a different way depending on forest-type classes. Results on the affected area from the two sensors were closer in the case of Portugal although in this case, MERIS tended to underestimate the damaged area. The best per forest-type class result is for the most abundant specie *Pinus pinaster*, while the worst result is for the second more abundant forest specie *Quercus suber*.

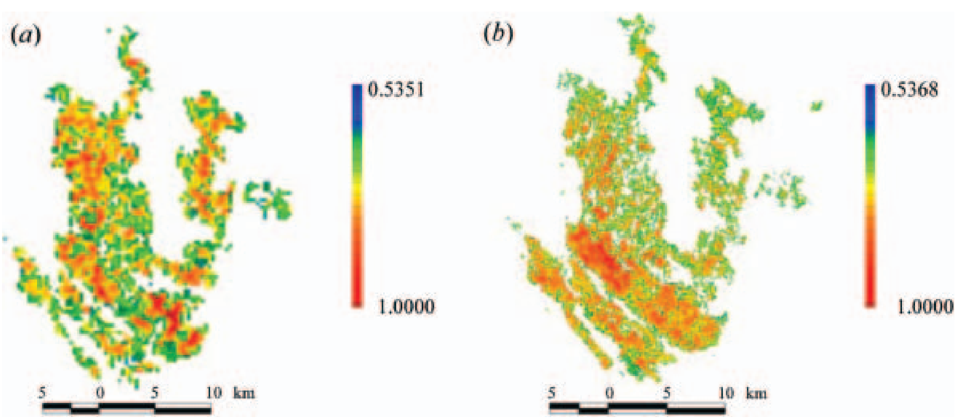

Figure 4. *(a)* MERIS-derived and *(b)* SPOT5-derived level-of-damage within the fire scar.

Table 1. Valencia de Alcántara forest fire statistics. Comparison between Envisat -MERIS and SPOT5-HRG. Relative difference calculated as the ratio between the difference between MERIS and SPOT5 estimations and the SPOT5 estimation.

	Envisat–MERIS (ha)	SPOT5-HRG (ha)	Relative difference (%)
Affected area	23 211.0	21 840.4	+6.28
Spanish affected area	16 176.5	13 988.1	+15.64
Portuguese affected area	7 034.5	7 852.3	−10.41
Spanish forested affected area	7 834.2	7 418.0	+5.61
Affected *Pinus pinaster* [a]	3 296.5	3 462.0	−4.78
Affected *Quercus pyrenaica* [a]	939.7	715.8	+31.3
Affected *Quercus ilex* [a]	591.7	652.9	−9.78
Affected *Quercus suber* [a]	2 520.0	2 059.7	+22.35
Affected *Castanea sativa* [a]	507.5	456.0	+11.29

[a] Forest species evaluated only within the Spanish territory.

4.2 *Relationship between degree of affection field data and satellite-derived level-of-damage*

One of the main objectives of the present work was to investigate into the capability of Envisat-MERIS and SPOT5-HRG data to map forest fire level-of-damage. In doing so, data from the post-fire ground survey (ground plots) were compared with data from the two developed level-of-damage maps (Envisat-MERIS and SPOT5-HRG). Another key point was the investigation into the relationship between the two satellite estimations themselves.

Ground fire severity data from the 74 sample plots had to be compared with the resulting MERIS-derived and SPOT5-HRG-derived level-of-damage images. Ground fire severity is a discrete variable ranging between 0 and 3 (as explained in section 3.1), while satellite-derived level-of-damage is a continuous variable ranging between 0 and 1.0 (before applying thresholds). The latter included values for unburned pixels since ground plots were collected all around the study area. For comparison purposes, it was necessary to reclassified satellite-derived level-of-damage Envisat-MERIS and SPOT5-HRG images into four-class maps (unburned, low, moderate and high). Such reclassification process was carried out using two different methods: (i) performance of thresholds (see table 2) based on the shape of the histograms resulting from matched filtering, and (ii) applying four-class unsupervised classification using the IsoData algorithm implemented on ENVI 4.1. Table 3 shows the distribution among the different fire severity classes for both MERIS and SPOT5-HRG using the two mentioned reclassification methods.

Once satellite-derived maps were reclassified, contingency tables were obtained in order to compare reclassification results with ground data. The Chi-square (χ^2) test

Table 2. Class limits for the reclassification of satellite-derived fire severity images into four-class maps.

Fire severity range	Fire severity class
0.0 – minimum	0 (unburned)
minimum – 0.7	1 (low)
0.7–0.8	2 (moderate)
0.8–1.0	3 (high)

Table 3. MERIS-derived and SPOT5-HRG-derived reclassified maps: distribution among fire severity classes.

	MERIS-derived (ha)		SPOT5-HRG-derived (ha)	
Fire severity class	Thresholds	IsoData	Thresholds	IsoData
0	94 401.0	94 401.0	95 771.6	95 771.6
1	7 713.0	8 091.0	5 843.5	5 843.5
2	9 513.0	8 451.0	8 871.0	8 871.0
3	5 985.0	6 669.0	7 125.9	7 125.9

was performed to check that both datasets were not independent, and the Overall Accuracy, the Kappa coefficient and the Kendall (τ) and Spearman (r) rank correlation coefficients were obtained to analyse the degree of association between the two sets of data. Kappa varies between 0 and +1, where +1 means the variables match perfectly. τ and r both range from −1 (complete disagreement) to +1 (perfect agreement). Results are presented in table 4. As expected, the relationship between MERIS-derived level-of-damage and ground data was weaker than between SPOT5-HRG-derived level-of-damage and ground data. This was an expected result since Envisat -MERIS produces one figure every 9ha, which exceeds the reasonable and affordable limits of any ground plot.

Besides comparison between satellite-derived and ground-measured fire severity, a general comparison between MERIS-derived and SPOT5-derived level-of-damage was carried out resulting in a 71.55% coefficient of determination, as shown in figure 5. This analysis was performed by rescaling SPOT5-derived level-of-damage image to MERIS pixel size using a 'pixel aggregate' re-sampling method. As shown in figure 5, continuous values were kept for comparison between satellite estimations. As expected from the analysis of figure 3, data in figure 5 appear clustered in two groups, one for unburned pixels (lower cluster) and the other one for burned pixels (upper cluster), with a very small number of outliers.

4.3 *Relationship between forest type and satellite-derived level-of-damage*

MERIS-derived and SPOT5-derived level-of-damage information was also compared with information on forested land-cover classes as derived from the Spanish NFM (1:50 000). The objective was to check to what extent the degree of damage was related to a particular type of forest or tree species, in the context of the study area. During the field trip, it was observed that pine forests tended to appear ravaged. This point was not surprising since pine forests were monospecific, densely

Table 4. Statistics measuring the degree of association between satellite-derived and ground-measured fire severity.

	χ^2 test	Overall accuracy (%)	Kappa coefficient	Kendall coefficient	Spearman coefficient
MERIS + thresholds	$p<0.01$[a]	51.4	0.35	0.584	0.658
MERIS + IsoData	$p<0.01$[a]	50.0	0.33	0.582	0.656
SPOT5 + thresholds	$p<0.01$[a]	70.3	0.59	0.770	0.834
SPOT5 + IsoData	$p<0.01$[a]	70.3	0.59	0.770	0.834

[a]Since the p-value is less than 0.01, we can reject the hypothesis that both datasets are independent at the 99% confidence level.

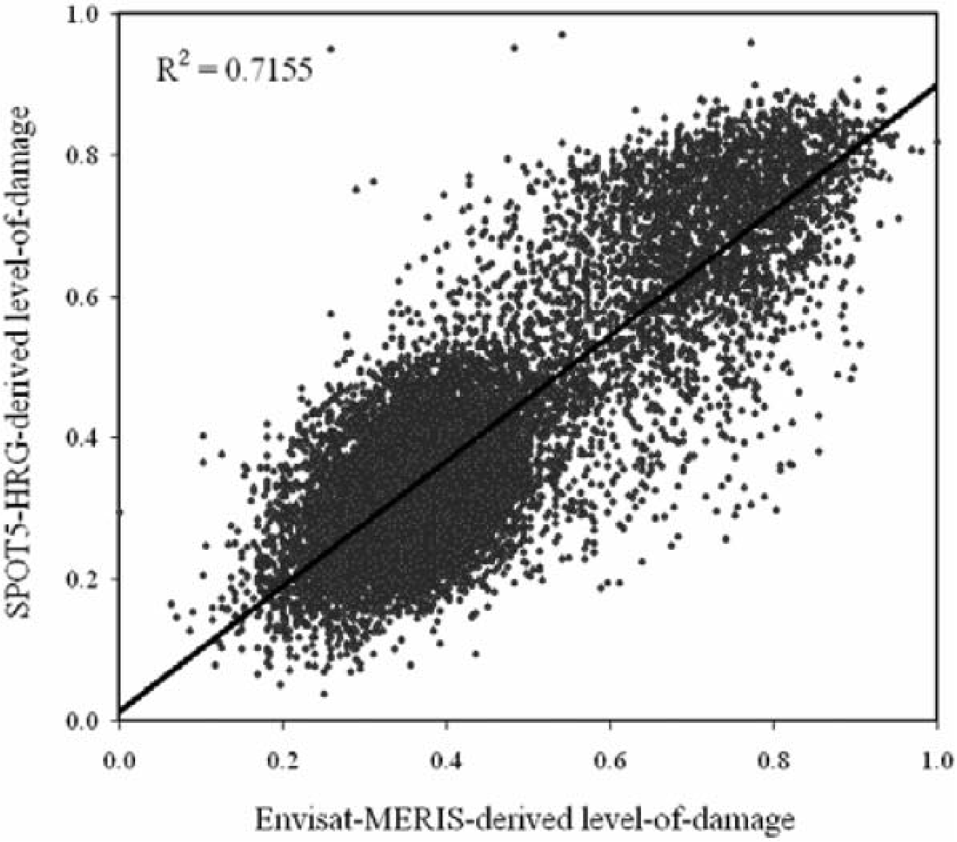

Figure 5. SPOT5-derived level-of-damage *versus* MERIS-derived level-of-damage and coefficient of determination between variables.

populated and almost untreated. However, all these subjective impressions needed to be investigated.

The first analyses carried out on MERIS and SPOT5-HRG level-of-damage information revealed that there was indeed a link between the forest type and the degree to which the land-cover was affected, with most forest types seemingly affected by wildfire in a characteristic manner. This tendency might be peculiar to the study area and might be different in other sites. Five forest types were analysed, each dominated by a single tree species: pine (*Pinus pinaster*), sessile oak (*Quercus pyrenaica*), holm oak (*Quercus ilex*), cork tree (*Quercus suber*) and chestnut tree (*Castanea sativa*). Mean affection values were calculated for each forest type using both MERIS and SPOT5-HRG level-of-damage information. In both cases, pine forests were the least resistant while holm oak forests were the most fire-resistant. The other three forest types showed an intermediate degree of affection that varied between sensors.

Another set of analyses was based on contingency tables for which the degree of affection was divided into two classes: 'low to moderate damage' (values ranging between minimum and 0.8) and 'high damage' (values ranging between 0.8 and 1.0). MERIS-derived level-of-damage data analysed through the use of contingency tables produced the following order of fire-resistance: pine forests (the least resistant), cork tree forests, chestnut tree forests, sessile oak forests and holm oak forests (the most resistant). SPOT5-derived level-of-damage information produced almost the same result: pine forests, chestnut tree forests, sessile oak forests, cork tree forests and holm oak forests.

5. Conclusions

Satellite remote sensing may be successfully involved in burned land mapping and fire severity mapping since it provides a means of gathering the needed information from the Earth's surface (Koutsias *et al.* 1999). Results achieved so far show that satellite-based estimations of wildfire damage over forested areas can be extremely useful not only in establishing the scale of the damage, but also for the subsequent forest renewal projects and for subsidy management. Envisat -MERIS and SPOT5-HRG data can also be used to good effect for future forestry planning activities, since more fire-resistant forest types—as established by this or similar studies—should be proposed for new plantations in vulnerable areas.

Although SPOT5-HRG data have better spatial resolution, the resulting MERIS-FR estimations would efficiently and regularly provide updated fire statistics and fire severity assessments at a low cost and in near real time, thanks to the new capabilities of ESA in providing MERIS data a few hours after acquisition. Such results would be of great interest at regional to national scales, results that are usually unaffordable using high resolution data (SPOT5-HRG).

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