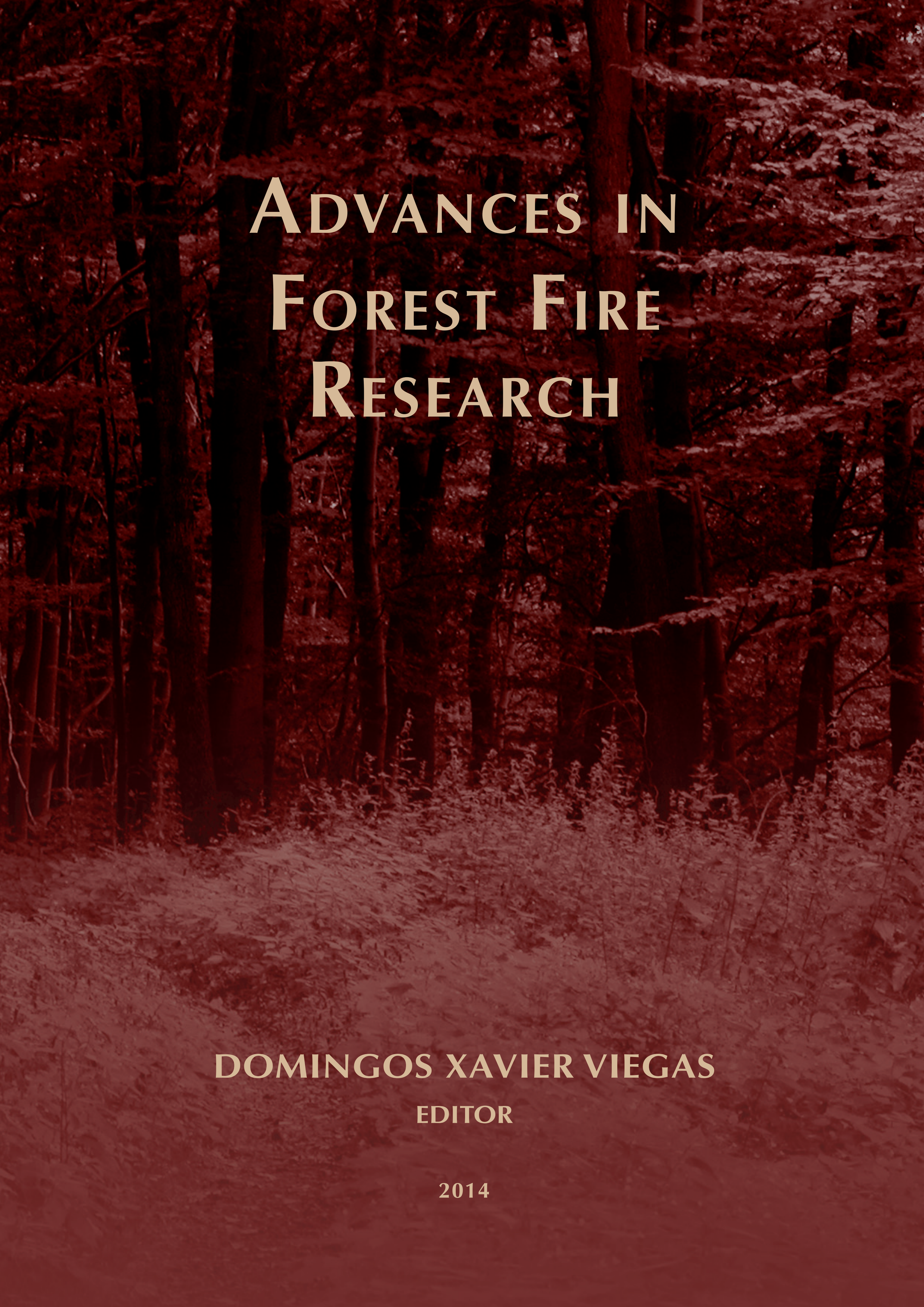

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Determining the economic damage and losses of wildfires using MODIS remote sensing images

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Abstract
The economic evaluation of damage and losses of the areas affected by forest fires requires comprehensive studies covering a wide range of natural resources. The assessment of fire impacts requires the individualized study of each resource, such as timber resources, fruit production and hunting activity, and the analysis of their net value change based on fire intensity and ecosystem resilience. As a consequence, this concept of net value change extends the study beyond an economic valuation, integrating two concepts, the value of the resource and fire behavior. However, field sampling on large fires becomes complex because of the costs involved in field tasks and the time that will elapse before the assessment is available.
The incorporation of satellite imagery to the economic valuation of fire impacts provides a new tool of undoubted interest. This paper details the methodology and the results obtained in the economic assessment of two medium (between 200-500ha) and two large fires (more than 500 ha) in the south of Spain. MODIS data were suitable for mapping medium and large fires (more than 200 ha). The advantage of using MODIS satellite images in relation to other remote sensors lies in the free download (zero cost) and temporal resolution. As other studies have shown, the normalized vegetation index was not presented as the best identifier of the burned area. However, RdNBR index allowed us to obtain reliable relationships between its value and the depreciation ratio for each resource due to the differences among resources based on fire intensity.
Economic resources valuation and MODIS images (pre and post-fire) can be integrated into Geographic Information System (GIS), in order to obtain, in a geo-referenced way, the economic value per hectare resulting from fire impact. This tool should provide a procedure to help improving fire management and take more appropriate decisions about budg*et al*location and rehabilitation of areas affected by fires. Given current economic constraints, the use of a geo-referenced tool with free download and regular update (MODIS) allows us to the inclusion of changes, improvements and temporal or spatial adaptations according to the needs of forest managers. The methodological approach for assessing the economic impact of forest fires provided allows the application of this simple and flexible technique to any territory by previous economic valuation of natural resources presented in the interesting area.

***Keywords**: Economic losses; net value change, vegetation indices, remote sensing, fire management*

1. Introduction

Forest fires are a major factor of environmental transformation in a wide variety of ecosystems (FAO, 2007). Although fire has been used since ancient times in crop rotation, agricultural plowing and pasture creation for the purpose of livestock use, socio-economic changes have led to an abandonment of traditional uses. This neglect results in a greater accumulation of scrub (Perez, 1990; Rodriguez y Silva and Molina, 2010), which, along with the accentuation of climate conditions (Piñol *et al*., 1998), are transforming fire into a threat to the biodiversity and conservation of Mediterranean ecosystems (Brook *et al*., 2003).
Remote sensing is commonly used for monitoring wildfires using various space-borne sensors, such as Landsat and MODIS (Chuvieco *et al*. 2005; Devineau *et al*., 2010). MODIS (Moderate Resolution

Imaging Spectroradiometer) data were suitable for mapping medium and large (50-500 ha) burn scars that accounted for the majority of all fire-damaged forests (Morton *et al*., 2011). MODIS makes up to four daily observations from each of the Terra and Aqua satellites providing consistent data on fire development with high temporal frequency. The use of MODIS satellite images enabled us to map wildfires at a national scale due to the high temporal resolution of the sensor (Levin and Heimowitz, 2012). In other works, MODIS has been used to the classification of fires into headfire and backfire types in assessing pollutant emissions to the atmosphere (Smith and Wooster, 2005). The incorporation of satellite imagery to the economic evaluation provides, in a novel way, a tool of undoubted interest to accurately identify the natural resources affected by fire (Rodríguez y Silva *et al*., 2009, 2012a). The advantage of using MODIS satellite imagery lies in the availability of real-time information at zero cost.

The economic evaluation of damage and losses of the areas affected by forest fires requires comprehensive studies covering a wide range of natural resources. The valuations of natural resources tend to underestimate the real value of the forest (Constanza *et al.*, 1997). Unlike traditional economic activity, the forest environment is characterized by the extraordinary relevance of externalities that involve harm or benefits of considerable magnitude to others (Riera, 2000). From forest management standpoint, it is necessary to express all the natural resources in monetary terms. The economic valuation requires the identification of the "net change value" of the resources affected by fire. As a consequence, this concept of "net value change" extends the study beyond an economic valuation, integrating two concepts, the value of the resource and fire behavior (Rodríguez y Silva and González-Cabán, 2010).

Wildfires are the most important disturbance in the Mediterranean area causing damages to tangible assets, environmental services and landscape goods. The spatial assessment of fire impacts is indisputable in the identification of effective rehabilitation actions. However, this evaluation becomes complex when the size of the affected area makes gathering the information unfeasible, mainly because of the costs involved in obtaining the information and the time that will elapse before the final assessment is available. The aim of this paper is to assess the economic fire impacts of medium and large fires based on satellite images and fire intensity level. One of the most difficult concepts to value the economic impact of fire on natural resources is determining the net value change or economic value loss. MODIS images identify value change based on the differences in spectral information based on fire behavior. The socioeconomic vulnerability model was incorporated into a Geographic Information System (GIS) that facilities the development of spatiotemporal tracking cartography, at both the individual resource level and the integrated ecosystem vulnerability level. The impacts valuation using satellite images and GIS achieves in a versatile geo-referenced tool understanding of the forest system vulnerability to wildfires, at virtually real time.

2. **Methods**

The economic evaluation of fire impacts by MODIS images has been carried out for four large fires in Andalusia, in the south of Spain. These four fires provide a wide range of Mediterranean ecosystems and topographical characteristics: burned area from 275 to 7,300 ha, range of altitudes between 423 and 1,200 m meters above sea level and different stand areas (*Quercus ilex*, *Castanea sativa*, *Alnus glutinosa*, *Pinus pinea* and *Pinus pinaster*) and treeless (chaparral, *Cistus* genus, *Pistacia lentiscus*, *Rosmarinus officinalis* and *Juniperus oxycedrus*).

The economic impact assessment of a large forest fire requires the following phases of analysis and development:

a) Economic valuation of natural resources
b) Spatial identification of different damage levels
c) Identification of the net value change in the resources
d) Economic valuation of fire impacts

2.1. Economic valuation of natural resources

Although economic valuation of natural resources must incorporate three types of resources: tangible assets, environmental services and landscape goods, this paper only includes tangible assets covering timber and non-timber resources. The methodology for the evaluation of timber resources consists of an algorithm integrating the method in the National Fire Management Analysis System (NFMAS) developed by the USDA Forest Service and the method used by the Spanish Forest Service (Rodríguez y Silva *et al*., 2012b). NFMAS is based on the concept of natural restoration while Spanish system considers artificial restoration based on stand development stage and rotation age of the species.

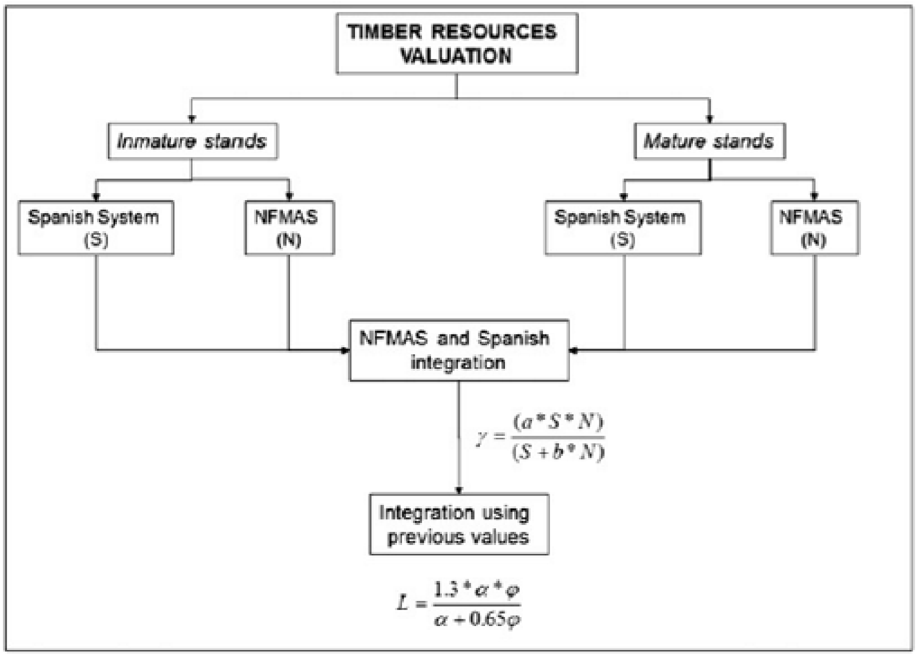

Figure 1. Methodological scheme for the valuation of timber losses (Rodríguez y Silva et al., 2012b)

Non-timber losses should be calculated depending on the generated annual income from resources production, such as pasture, acorn and pine nut production (Table 1). A problem exists because of the number of years without resource production or vegetation resilience (Molina *et al*., 2011; Roman *et al*., 2013). Valuation of grassland impact requires information on the available production, nutritional value of the grass and the carrying capacity of the area. On the other hand, fruit production per hectare is given by the tree production and the canopy closure adjusted for site index and phytosanitary condition. Finally, the hunting resource is based on the acquisition of a hunting assessment by updating the annual profit plus the stock or replacement value of the reproductive wildlife (Zamora *et al*., 2010).

Table 1. Mathematical formulations used for economic valuation

Resource	Formula	Potential status	Source
Timber	$\gamma = (a*S*N)/(S+b*N)$	Immature and mature stands	Rodríguez y Silva *et al*. 2012
	$S = C_0*t\ [r^e + i(r^e - 1)] + F*(r^e - 1)$	Immature stands	
	$N = [(P*V*1.025^y)/1.04^y]*[1-(1.025/1.04)^e]*[1 + M*c*t]$	Immature stands	
	$S = [P*V - P_1*V_1] + P*V\ [(r^{(R-e)} - 1)/(r^{(R-e)})]$	Mature stands	
	$N = V*c*t[C*P + (1 - C)*P_1]$	Mature stands	
Firewood; fruit production	$L = A_p*P_r*[((1+r)^y - 1)/(r*(1+r)^y]$	Mature stands	Martínez, 2000; Molina *et al*., 2011
Pasture production	$L = V*[((1+0.06)^n - 1)/(0.06*(1+0.06)^n]$	Livestock and/or game area	Martínez, 2000; Molina *et al*., 2011
Hunting activity	$L = V*[((1+0.06)^n - 1)/(0.06*(1+0.06)^n] + S$	Game area	Zamora *et al*., 2010

where " γ " is the timber valuation (€/ha), “S” is the valuation according the Spanish system (€/ha), “N” is the valuation adapted from NFMAS (€/ha), “a” takes the value of 1.7 or 2.6 according to protection or recreational function, or timber forest respectively, “b” takes the value of 0.85 or 0.25 base on the same reasons, “C_0” is the reforestation cost per hectare (€/ha), “t” is the percentage burned stand based on fire behavior, “r” is the compound annual interest rate and depends on species growth rate: fast growth (1.06), medium growth (1.04), slow growth (1.025) and very slow growth (1.015); “e” is the estimated stand age, “i” is the annual silvicultural cost factor and depends on species growth rate: fast growth (1.27), medium growth (1.1) slow growth (1.1) and very slow growth (0.93), “P” is the price of the timber (€/m^3), "V" is the timber volume (m^3/ha), “y” is the time or years remaining in the harvesting rotation or senescence age, “M” is the tree mortality coefficient depending on fire intensity, “c” is the percentage of immature or mature timber in stand, “P_1” is the price of affected timber with commercial use (€/m^3), “V_1” is the volume of burned timber (m^3/ha), “R” is the rotation age, “C” is the percent of non-commercial timber, “L” is the resource loss (€/ha), “A_p” is the annual production (kg/ha), “P_r” is the estimated resource price (€/kg), “V” is the annual income given the carrying capacity of the site (€/ha), “n” is the estimated number of years until recovery (vegetation resilience), “S” is the reproductive stock (€/ha)

2.2. **Spatial identification of different damages levels**

The spatial and spectral information from satellite images before and after fire let us to identify fire severity (Chuvieco *et al*., 2008). MODIS images were assessed in order to characterize fire impacts and to relate them with land cover. The spatial identification of the different damage levels was performed using MODIS images (Terra and Aqua) for a previous date as well as for a post-fire date. The MODIS products (both pre and post-fire) were downloaded from the United States Geological Service’s LP DAAC Server (https://lpdaac.usgs.gov/get_data/data_pool). These images were already geometrically corrected. The original reference and coordinate system was transformed to the ETRS89 30N system making the overlapping of the images with the fire perimeter in vector format. The identification of damage levels was obtained based on the spectral and spatial differences between pre and post-fire images. Figure 2 shows a framework for the methodology proposed in this paper.

The surface reflectance, both for the Terra and Aqua platforms, was identified in the electromagnetic spectrum of 620-670nm (Red-NIR) for band 1, and 841-876nm (NIR) for band 2. In the case of images with a spatial resolution of 500 meters, the band 7 used ranged from 210-215nm. Geo-referencing and adjusting of the final fire perimeter was performed with ArcGIS© software, keeping a 150-meter tolerance buffer in order to include the effect of the proximity to the burned area. In order to harmonize MODIS bands (1, 2 and 7) and land use cartography for the calculation of the fire impacts, all inputs were resampled from original spatial resolution to 25 m (cell size = 0.625 ha).

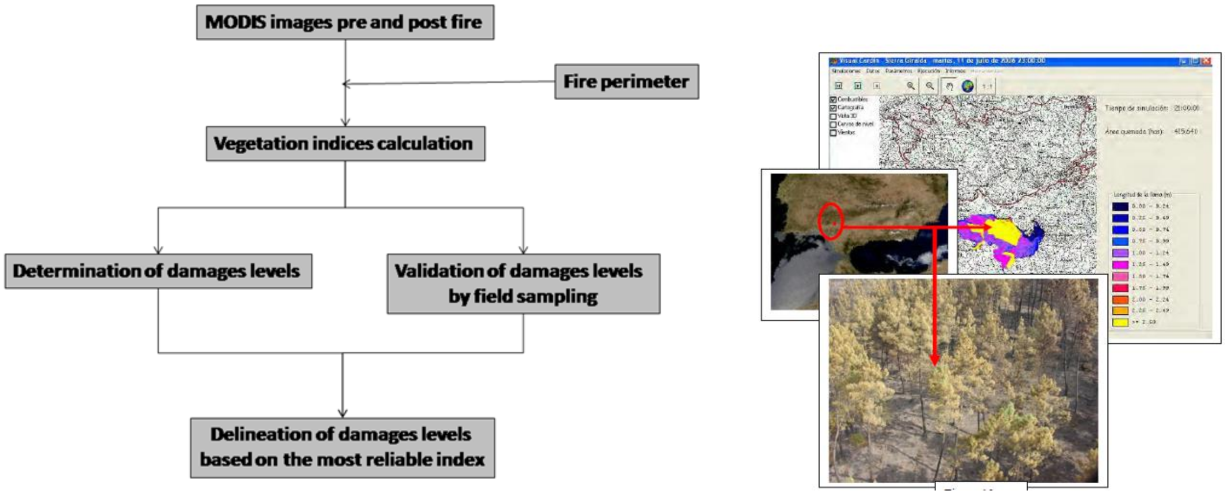

Figure 2. Framework of the methodological proposed in this paper

Three vegetation indices were considered: Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio (NBR) and a relative differenced Normalized Burn Ratio (RdNBR).The calculation of these indices requires mid-infrared (MODIS band 7) and near infrared (MODIS band 7) information. MODIS band 7 was very important due to its intrinsic ability to identify fuel moisture.

At the Red-NIR spectral space, NDVI (Chuvieco *et al*., 2002) was computed as follow:

$NDVI = (\rho_{NIR} - \rho_{R}) / (\rho_{NIR} + \rho_{R})$
where ρ_{NIR} is the reflectance in the NIR (MODIS band 2) and ρ_{R} is the reflectance in the RED (MODIS band 1).

In the NIR-SWIR spectral space, NBR (Key and Benson, 1999) was calculated as follow:

$NBR = (\rho_{NIR} - \rho_{LSWIR}) / (\rho_{NIR} + \rho_{LSWIR})$
where ρ_{NIR} is the reflectance in the NIR and ρ_{LSWIR} is the reflectance in the SWIR (MODIS band 7).

In both vegetation indices the value range oscillates between -1 and 1. While values close to zero generally correspond to bare soil areas, positive values represent shrublands or grasslands (lower positive values) and forest lands (values close to one). The identification of the damage level of each "cell" (0.625 ha) was estimated by the differences in the values of vegetation indices, pre and post fire:

dNDVI = PreFire NDVI – PostFireNDVI
dNBR = PreFire NBR – PostFire NBR

Since chlorophyll contents vary due to vegetation type and density, each absolute differenced image should ideally be stratified by pre-fire vegetation type and independently calibrated. Therefore proposed the creation of a relative differenced NBR (RdNBR) to remove the biasing of the pre-fire vegetation by dividing dNBR by the square-root of the pre-fire NBR as follows (Miller and Thode, 2007):

RdNBR = dNBR / [Square Root (ABS (PreFire NBR/1000)]

We scale NBR by 1,000 to transform the data to integer format (Key and Benson, 2005); therefore the pre-fire NBR must be divided by 1,000 in the RdNBR formula. Positive RdNBR values remain representing a decrease in vegetation cover, while negative values represent an increase in vegetation cover.

2.3. Identification of the net value change in the resources

The economic assessment of fire impacts on natural resources requires knowledge of the fire severity. The net value change in the resources is computed as a function of fire severity, which is determined by Fire Intensity Level (FIL) (Molina *et al*., 2011; Rodriguez y Silva *et al*., 2012b). To estimate the rates of depreciation for each resources based on fire behavior we used the following 13 large fires (year of fire in parenthesis) in Andalusia: Huétor (1993), Aznalcollar (1995), Los Barrios (1997), Estepona (1999), Cazorla, Segura and Las Villas Natural Park (2001, 2005), Ojen (2001), Aldeaquemada (2004), Minas de Río Tinto (2004), Alajar (2006), Obejo (2007), Cerro Catena (2009) and Cerro Vértice (2011). For the valuation of hunting activity, information from Monfragüe National Park, Aldeaquemada and Minas de Río Tinto were used to test the annual hunting profit and number of years until recovery (vegetation resilience) (Zamora *et al*., 2010).
Different sampling plots (10 and 15 m square plot) were established according to forest characteristics and average flame length in each fire event. We used flame length as a simple parameter "in situ" for fire severity. The creation of a direct relationship between fire severity and flame length increases the flexibility and simplicity of this methodological approach. In addition, a photographic overview was taken as a virtual key to identify vegetation resilience.

2.4. Economic valuation of fire impacts

We used Geographic Information Systems (GIS) to assess the socio-economic impacts on natural resources. The use of GIS allows us the option to link the economic value of natural resources and damage levels obtained by MODIS images. An extrapolation of sampling depreciation rates for each damage level could be extrapolated to large burned area with the help of remote sensing. The depreciation rate is estimated individually for each resource based on damage level depending on fire intensity. The integration of both economic value and real fire impacts provides the economic vulnerability of each resource. Final economic vulnerability is the sum of the vulnerabilities of the resources present in each burned area. Economic vulnerability cartography was developed showing fire impacts by hectare.

3. Results

3.1. Economic valuation of natural resources

It was necessary to characterize vegetation (combination between stand cover and understory association) to identify the natural resources presented in each area. In stand areas, immature and mature condition could be determined from the rate of growth and rotation length, as well as approximate stand age that is necessary for some resources valuations. Once the vegetation structure was characterized, a spreadsheet was used to identify the economic vulnerability of each area based on the mathematical formulations (Table 1). This characterization was related to dominant species, as a consequence, to the ecosystem resilience, that can be defined as the time needed by a species to recuperate to its original condition as a result of fire. Resilience was assigned based on restoration planning (large fires in Andalusia) and the experiences in the maintenance of the preventive infrastructure in wildfire risk areas (Zamora *et al*., 2010).
As an example of the application of this methodological approach, we incorporated the economic valuation of natural resources from "Catena fire" (Table 2). Economical results indicated that timber is the most important resource (€ 194,093.17), given the natural condition of the *Pinus pinaster* and their longevity (over 100 years in some stands). Tangible assets valuation reaches to € 263,568.69, showing a value per unit area of 1,261.1 €/ha.

Table 2. Tangible assets valuation for one example fire

Resource	Valuation (€)	Valuation per unit area (€/ha)	Representativeness (%)
Timber	194,093.17	928.68	29.35
Non-timber resources	60,771.17	290.77	9.19
Hunting activity	8,704.35	41.65	1.32

3.2. Spatial identification of different damages levels

MODIS images were assessed in order to characterize fire damages levels based on field sampling plots. In order to the size of the fire, we can identify four or six fire intensity levels according to the flame length (directly related to the fire line intensity) and spatial resolution. In this sense, four fire intensity levels were differentiated by medium fires (between 200 and 500 ha):

- Damage level I: this level corresponded to a flame length lower than 3 meters
- Damage level II: this level corresponded to a flame length between 3 and 6 meters
- Damage level III: this level corresponded to a flame length between 6 and 10 meters
- Damage level IV: this level corresponded to a flame length exceeding 10 meters

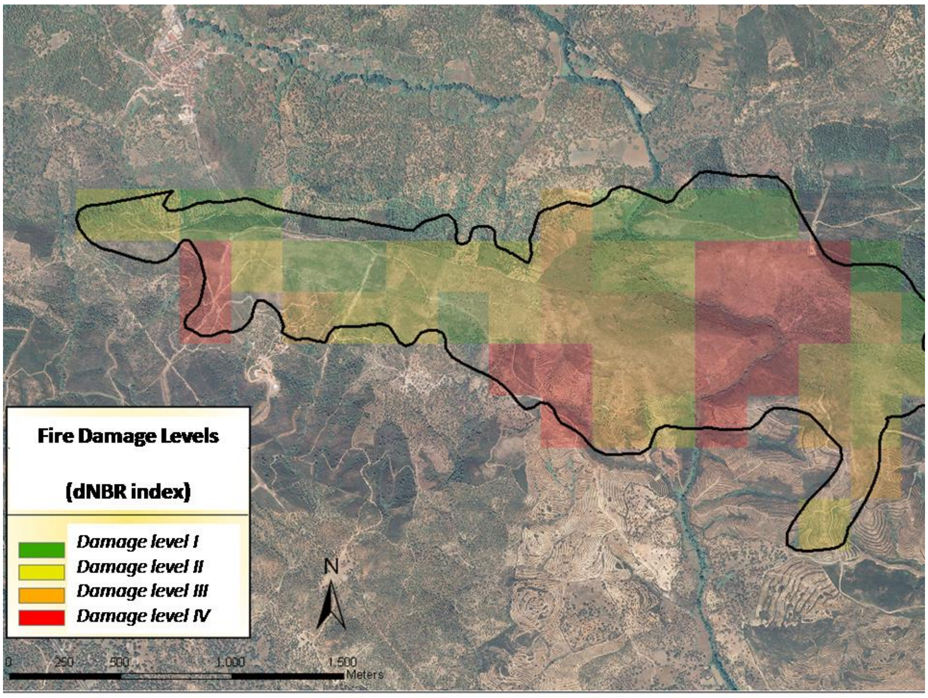

Figure 3. Fire damage levels from medium fire (275 ha)

In the case of large fires (more than 500 ha), the damage scale was extended to six categories due to the large sampling area and the most different fire behavior:

- Damage level I: this level corresponded to a flame length lower than 2 meters
- Damage level II: this level corresponded to a flame length between 2 and 3 meters
- Damage level III: this level corresponded to a flame length between 3 and 6 meters
- Damage level IV: this level corresponded to a flame length between 6 and 9 meters
- Damage level V: this level corresponded to a flame length between 9 and 12 meters
- Damage level VI: this level corresponded to a flame length exceeding 12 meters

The selected index should have adequate differences among damage levels, to avoid potential omission error in the automatic remote sensing process. The observed behavior of the different indices, regarding the identification of different damage levels, was heterogeneous. In general, better results were obtained with NBR index in relation to NDVI indices, since it allowed better discrimination and contrast of the fire impacts (Figure 4). Pre-fire and post-fire values (dNDVI) showed a difference (0.128) higher than dNBR (Terra bands 2 and 7) due to the post-fire photosynthetic activity. The indicator RdNBR allowed eliminating existent correlation between the result of the ratio and the pre-fire NBR value showing the most reliable relation between reflectance fire response and damage levels.

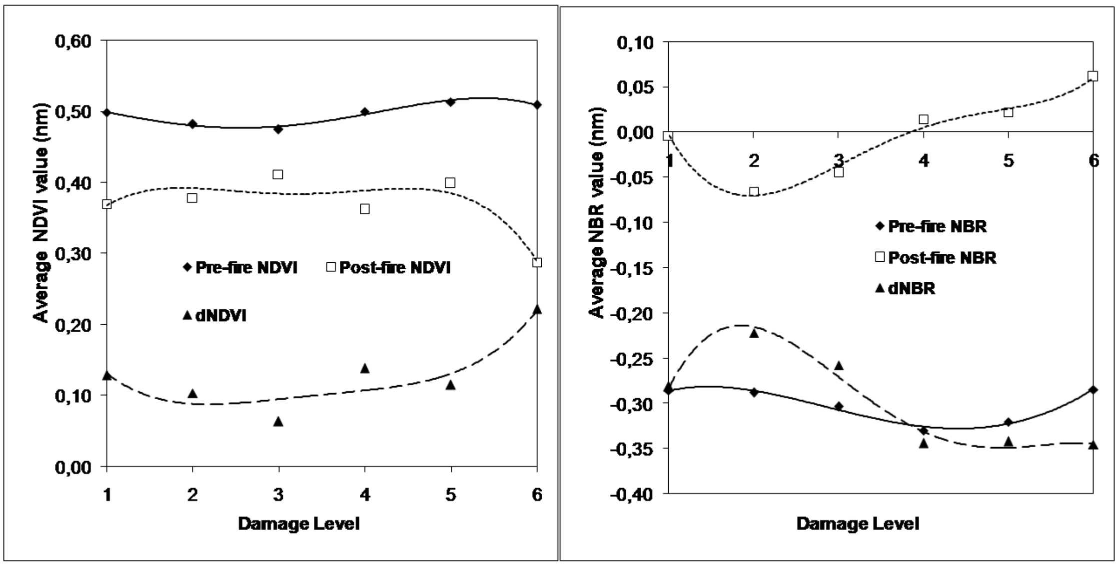

Figure 3. Comparison between dNDVI and dNBR for the same large fire

3.3. Identification of the net value change in the resources

The economic impact was determined by the fire intensity level. Therefore, a relationship had to be established between fire intensity level (directly related to flame length) and resource depreciation caused by the fire. The net value change expressed as different percentage intervals were from the result of some research projects and direct experiences from large fires in the region of Andalusia (Figure 4 and Table 4).

Figure 4. Sampling plots inventory on burned stand to determinate the net value change

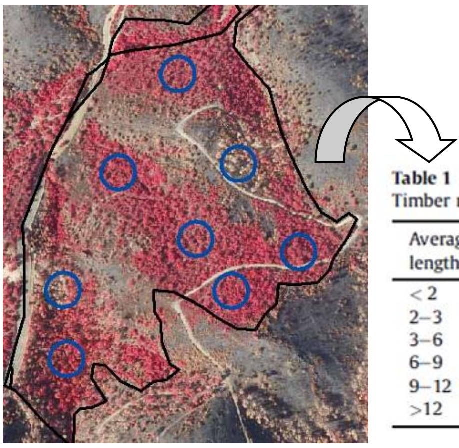

Table 1
Timber resource deterioration by fire intensity level.

Average flame length (m)	Fire intensity levels (FIL)	Timber resources deterioration (%)	Tree mortality coefficient (*x*)
< 2	I	8.33 (±6.58)	0
2–3	II	16.65 (±5.89)	0
3–6	III	38.58 (±6.27)	0.5
6–9	IV	57.85 (±13.74)	0.5
9–12	V	82.79 (±1.81)	1
>12	VI	89.41 (±2.82)	1

Table 4. Depreciation matrix (net value change for each resource based on fire intensity level)

Resource	Fire Intensity Level			
	I	II	III	IV
Timber	16.65 (±5.89)	38.58 (±6.27)	57.85 (±13.74)	89.41 (±2.82)
Firewood/fruit production	6 (±3.53)	14.2 (±5.03)	44.1 (±26.62)	73.40 (±5.65)
Hunting activity	40 (±17.67)	65 (±19)	84 (±15.27)	99 (±3.53)

*Depreciation matrix was more-detailed by other scientific papers: Rodríguez y Silva *et al*., 2012 (timber resource); Molina *et al*., 2011 (non-timber assets) and Zamora el al., 2010 (hunting activity)

Each resource change o depreciation value was adjusted with RdNBR index (the best index for the identification of the four damage levels) showing greatest correlation. We chose the logarithmic approach since it provides a reliable and easy way for the valuation of fire impact. In this sense, it is possible to provide the deterioration ratio (depreciation caused by fire and the residual economic benefits of vegetation unaffected) for each resource based on the spatial identification of the RdNBR index by MODIS images.

$y = a \ln(x) - b$

where " γ " is the net value change or depreciation ratio (%) and “x” is the value of RdNBR index

3.4. Economic valuation of fire impacts

MODIS data were suitable for mapping medium and large fires (more than 50 ha) similar to other studies (Morton *et al*., 2011). The spatial identification of damage levels with satellite imagery supported by a field inventory facilitates the extrapolation of the field information to the burned area (Devineau *et al*., 2008). The final step in the process, once the losses were determined and damage levels map was complete, was the preparation of a GIS-based data layer portraying the economic impacts to each studied fire (on a 25 x 25 m spatial resolution).

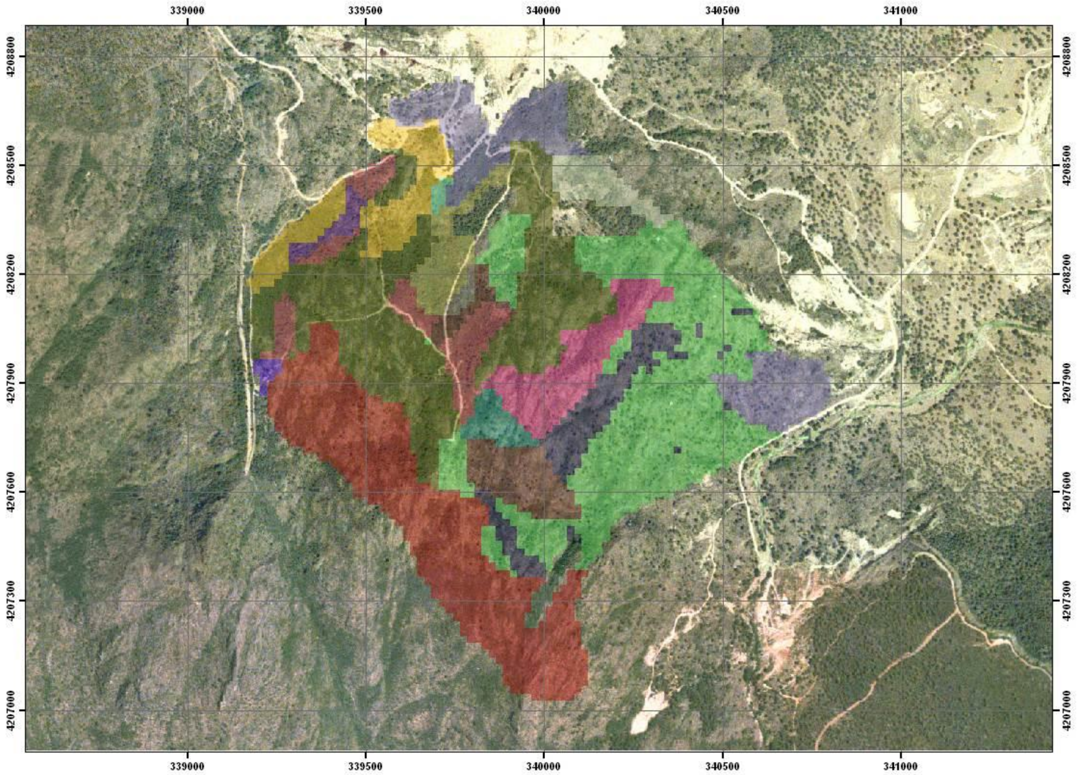

Figure 5. Economic valuation of burned area based on the socio-economic value of each ecosystem and the fire behavior

4. Conclusions

The integral valuation of forest ecosystems is essential for spatiotemporal planning conducted by forest managers. It is necessary to express non-timber resources in monetary terms. The incorporation of satellite imagery to the economic valuation of fire impacts provides a new tool of undoubted interest. The model should provide a sound procedure to help improving pre-fire management and take more appropriate decisions about rehabilitation of areas affected by fires.

The increasing demand for thematic mapping by government agencies with management responsibilities implies the need to develop tools and products based on Geographic Information Systems (GIS) and remote sensing. The use of GIS and remote sensing in spatial economic valuation provides flexibility when doing spatial ordination of the territory and increases the dynamisms of planning and systems protection tools. Given current economic constraints, the use of a geo-referenced tool with free regular updates (MODIS) allows us to the inclusion of changes, improvements and temporal or spatial adaptations according to the needs of forest managers.

5. Acknowledgements

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