# Chapter 27
# Remote Sensing Techniques for Monitoring Fire Damage and Recovery of Mediterranean Pine Forests: *Pinus pinaster* and *Pinus halepensis* as Case Studies

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## 27.1 Maritime and Aleppo Pine Forests in a World of Increasing Forest Fires

Pine and mixed pine forests are highly representative ecosystems of the Mediterranean Basin, providing goods and services to society. Both *Pinus halepensis* Mill. (Aleppo pine) and *P. pinaster* Ait. (maritime pine) are native pines in the Mediterranean region and dominate the current forested Mediterranean landscape (Fig. 27.1). Aleppo pine is the most widely distributed and abundant among the Mediterranean pines, covering nearly 7 million ha in the western, eastern and southern Mediterranean Basin. By contrast, maritime pine is a widespread conifer distributed mainly in the western Mediterranean Basin, across a broad range of elevation, climate and soil, resulting in significant genetic variation (Fernandes and Rigolot 2007).

Both species are very frequently affected by forest fires in Southern Europe (da Ponte et al. 2019). They are highly flammable and dominate forest ecosystems with high horizontal and vertical fuel continuity (Fernández-García et al. 2019a, b). This

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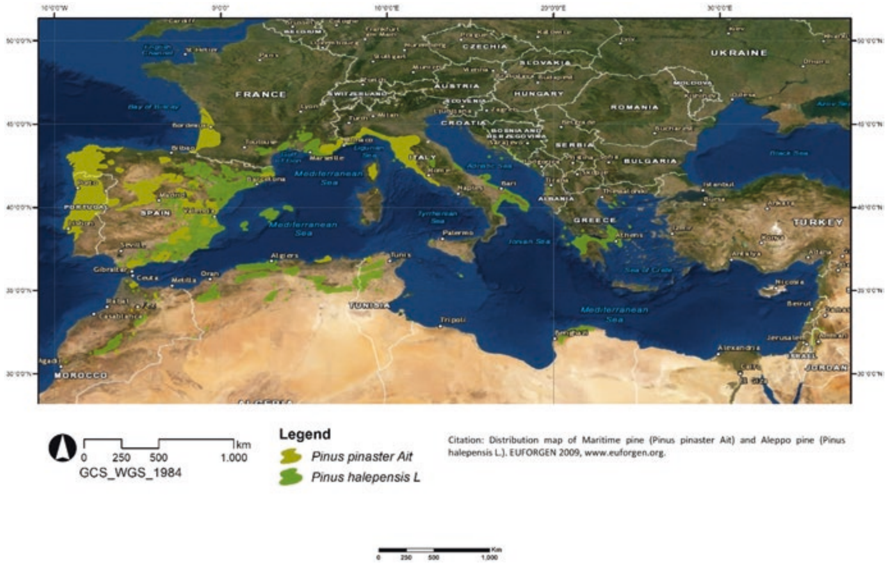


**Fig. 27.1** Distribution map of *P. halepensis* and *P. pinaster* in the Western Mediterranean Basin. (Data obtained from Euforgen.org)

fuel profile facilitates the occurrence of crown fires that cause widespread mortality (Calvo et al. 2008). The response of these species to fire has been classified into two categories that, in general, are considered complementary: (i) individual survival mainly characterized by thick bark, thick protected buds, self-pruning, deep rooting and rapid growth; (ii) stand resilience characterized by the presence of a large canopy seed bank (serotiny) that ensures abundant post-fire seedling recruitment (de las Heras et al. 2012). These mechanisms, in general, ensure the resilience of Mediterranean pine forests after fire, although it is also determined by population traits such as large cone crops, massive regeneration after fire, rapid juvenile growth and a short juvenile period (Calvo et al. 2008). *Pinus halepensis* and *P. pinaster* have demonstrated, as an adaptation to fire, a high number of serotinous cones, mainly in those populations with high fire recurrence (Moya et al. 2018). The seeds stored in serotinous cones are protected from fire and are massively released after the disturbance, finding proper conditions for germination, seedling establishment and growth (Calvo et al. 2013). This mechanism ensures the regeneration of *P. pinaster* and *P. halepensis* forests, with very high maritime pine seedling recruitment after only one fire (Calvo et al. 2008). However, Fernández-García et al. (2019b) and García-Llamas et al. (2019a) discussed the effect of burn severity on its regeneration process, because high severity could cause significant seed mortality. Another parameter of the fire regime that could significantly reduce post-fire regeneration of both pine species is fire recurrence. Recurrence of fires at short intervals induces a reduction in the regeneration capacity because these pines need at least 15 or 20 years to develop a fully productive canopy seed bank (Pausas et al. 2008).

In general, fire frequency and burn severity directly affect pine regeneration, but additional indirect effects are observed through changes in the abundance and composition of the woody understory community (Fernández-García et al. 2018a). Frequent fires facilitate the encroachment of understory species, such as resprouter species (e.g. *Erica australis* L.) (Calvo et al. 1998; Fernández-García et al. 2018b), which compete with pines for light, space and nutrients (Calvo et al. 2008, 2013; Taboada et al. 2017). Although these two Mediterranean serotinous pine tree species are adapted to certain fire regimes, rural abandonment, which induces an increase in fuel loads and continuity (García-Llamas et al. 2019b), as well as predicted climate change, with warmer and drier summers, lead to increases in fire frequency and burn severity that can hinder pine regeneration (Fernández-García et al. 2019b).

In studies carried out after two large wildfires (in 2012 in a forest dominated by *P. pinaster* in northwest Spain (León province) and in a forest dominated by *P. halepensis* in eastern Spain (Valencia) with different fire regime conditions of burn severity and fire recurrence), we have demonstrated the significant effects of both drivers on the recruitment and development of pine seedlings, as well as on competition between pine seedlings and woody understory species (Fernández-García et al. 2018a, b). Fire frequency significantly decreased the density, cover and height of pine saplings in the *P. pinaster* and *P. halepensis* forests (Figs. 27.2 and

**Fig. 27.2** *Pinus halepensis* seedling recruitment in the high burn severity and low recurrence scenarios

**Fig. 27.3** Strong woody understory regeneration in the *P. pinaster* forest under high burn severity and high recurrence scenarios

27.3). At the same time, burn severity mainly reduced the density of pine saplings. The negative effects of inter-specific competition between cover of woody understory species and pine regeneration is more important in high fire frequency scenarios (Fernández-García et al. 2019b).

## 27.2 Evaluation of Fire Damage in Mediterranean Pine Forests by Remote Sensing Techniques

The effects of fire on ecosystems are controlled by fire regime parameters, amongst other factors. In this sense, burn severity can alter the resilience of vegetation and soil properties, both of which are critical for post-fire forest management. It has also been identified as one of the most critical factors determining the ecological effect of fire on ecosystems (Tanase et al. 2011). Consequently, the timely generation of reliable maps of burn severity that reflect induced changes in vegetation and soil properties is a high priority for supporting post-fire decision-making in both the short and long term (Miller et al. 2009).

Traditionally, burn severity assessment has been based on field methods such as the Composite Burn Index (CBI) and the GeoCBI Index (Key and Benson 2006; de Santis and Chuvieco 2009). However, field methods are often expensive and

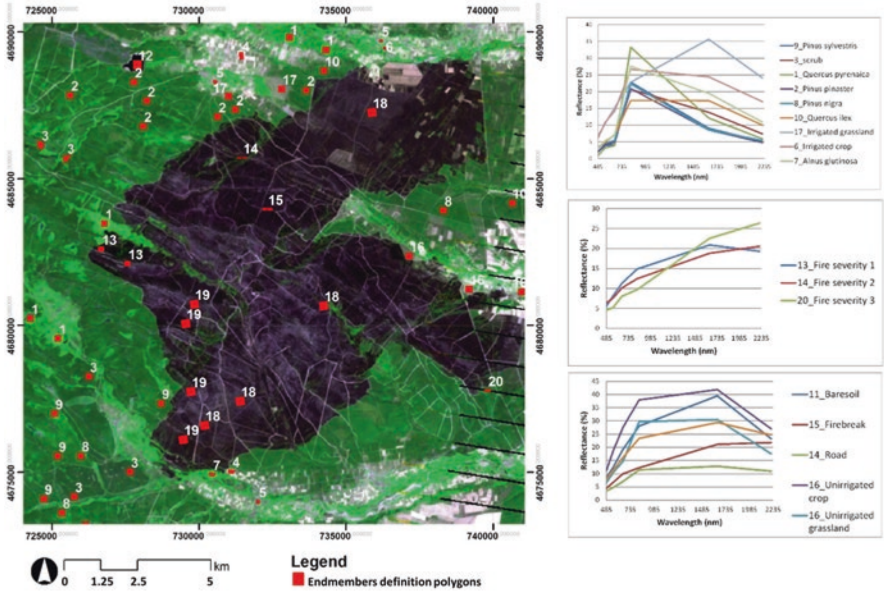


**Fig. 27.4** Left: Field plots to measure burn severity after the Castrocontrigo fire. (León, Spain) over a Landsat 7 (ETM+) RGB:741 color composition. Right: Spectral signatures of vegetation (upper), char (center) and soil (lower) included in the spectral library to unmix the Landsat data

time-consuming, and provide limited spatial and temporal representation of the ecological effects of fire. Fire causes substantial spectral and thermal changes to the earth's surface, associated with the consumption of vegetation and exposure of soil and charred stems, which can be captured by remote sensing sensors. Following a fire event, a dramatic reduction in near infrared reflectance (NIR, 700–1300 nm) and an increase in shortwave infrared reflectance (SWIR, 1500–2300 nm), both associated with carbonization and elimination of vegetation, is the principal information recorded by pre- and post-fire sensors. As an example, Fig. 27.4 displays the spectral library of the Castrocontrigo fire (León, Spain) in a Landsat 7 image one month after fire. Spectra 13, 14 and 20 are representative of the burned surfaces, and contrast with spectrum 2, associated with *P. pinaster*, the dominant species in the area.

In recent years, spectral indices based on remotely sensed data have been developed to map and monitor the effects of forest fires. Among them, the Normalized Burn Ratio (NBR) (based on NIR and SWIR spectral bands) and, in particular, differenced NBR (dNBR), is the most widely used index (Key and Benson 2006). Relative dNBR (RdNBR) has subsequently been proposed to eliminate the influence of pre-fire vegetation. It hypothetically enables creation of categorical classifications using the same thresholds for fires that occur in similar types of vegetation without the need to acquire data calibration for each fire (Miller et al. 2009). More recently, a new index for estimating burn severity, the relativized burn ratio (RBR)

**Table 27.1** Spectral indexes derived from Normalized Burn Ratio

| Acronym | Spectral index | Equation | Reference |
|---|---|---|---|
| NBR | Normalized burn ratio | $\frac{NIR - SWIR}{NIR + SWIR}$ | López-García and Caselles (1991) |
| dNBR | Differenced NBR | $prefireNBR - postfireNBR$ | Key and Benson (2006) |
| RdNBR | Relative dNBR | $\frac{dNBR}{\sqrt{ABS\left(prefireNBR / 1000\right)}}$ | Miller et al. (2009) |
| RBR | Relativized burn ratio | $\frac{dNBR}{prefireNBR + 1.001}$ | Parks et al. (2014) |

(Parks et al. 2014), has been proposed as an alternative to dNBR and RdNBR (Table 27.1).

Burn severity maps are usually obtained from these spectral indices (Arnett et al. 2015; Cardil et al. 2019; Fernández-García et al. 2018b; Harris et al. 2011; Lhermitte et al. 2011; McCarley et al. 2017; Quintano et al. 2018; Stambaugh et al. 2015, among others). In these maps, burn severity is represented by discrete thematic categories, generally distinguishing between unburned and low, moderate and high burn severity levels. Since the indices provide continuous data to classify severity into discrete categories, it is necessary to establish cut-off thresholds. The burn severity map of the Gátova fire (Fig. 27.5; Valencia, Spain) is based on the classification of a dNBR image (Landsat 8) using the thresholds proposed by Botella and Fernández-Manso (2017). Details 1–4 in Fig. 27.5 show the different levels of burn severity in a fire that occurred in Aleppo pine ecosystems in 2017.

From an ecological point of view, burn severity classification is closely linked to the time elapsed between fire occurrence and the measurement of fire damage. Thus, two different assessment intervals are distinguished: initial and extended, each one associated to different information content and functions. The initial assessment is the first opportunity to obtain an essentially complete ecological assessment of fire damage, since it is ideally performed immediately after the fire has been extinguished, and good quality data are also available. Elapsed time should range between fire occurrence and 8 weeks later (Key and Benson 2006). By contrast, the extended assessment is made during the first growing season after the fire. It enables assessment of the delayed survival of vegetation that has burned, but whose roots or stems remain viable and regenerate, and delayed mortality, where plants appear externally healthy immediately after the fire, but eventually die due to root damage. Therefore, the choice of assessment type depends on the objectives pursued.

New methodologies have been tested to improve burn severity estimates. Quintano et al. (2013) obtained a highly accurate estimate using Multiple Endmember Special Analysis (MESMA) fraction images instead of spectral indices. Their success is related to the characteristics of the short-term domain after the

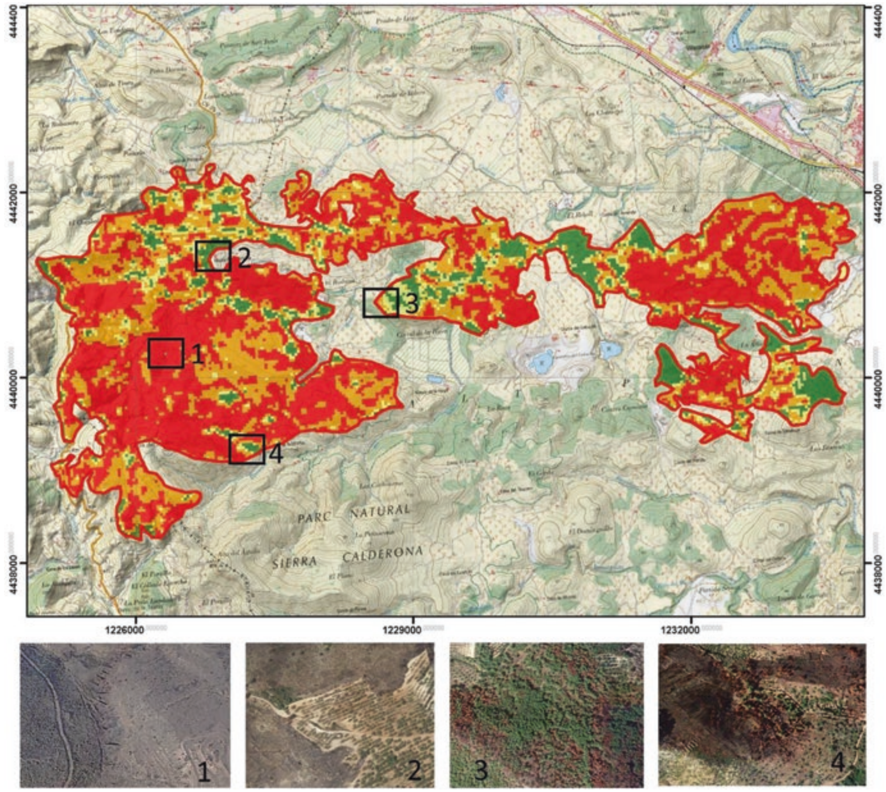


**Fig. 27.5** Burn severity map of the Gátova fire (Valencia) (red: high burn severity; orange: moderate burn severity; yellow: low burn severity; green: unburned). Details 1–4 represent the burn severity in the locations indicated on the map

fire that generally produces a mixture of vegetation, ash and burnt soil, which is essentially a sub-pixel question in the spatial resolution of commonly used multi-spectral sensors. Fraction images have a physical meaning; they estimate the fraction of the different land covers present in a pixel, thus making them easier to interpret. Other research works on post-fire burn severity mapping have been also based on fraction images, in particular on char fraction (Dennison et al. 2006; Fernández-Manso et al. 2019; Quintano et al. 2013, 2017, 2019; Tane et al. 2018; Veraverbeke et al. 2012, 2014).

Perhaps the most novel approach in the study of burn severity is that which is based on variables related to energy balance. Post-fire changes in vegetation, soil and water balance corroborate the impact of forest fires on the energy balance. Fire induces modifications in vegetation structure and species composition and alters latent heat flux, closely related to evapotranspiration, and other variables in the energy balance equation (Quintano et al. 2015). Evapotranspiration (ET), land surface temperature (LST) and land surface albedo (LSA) can discriminate different

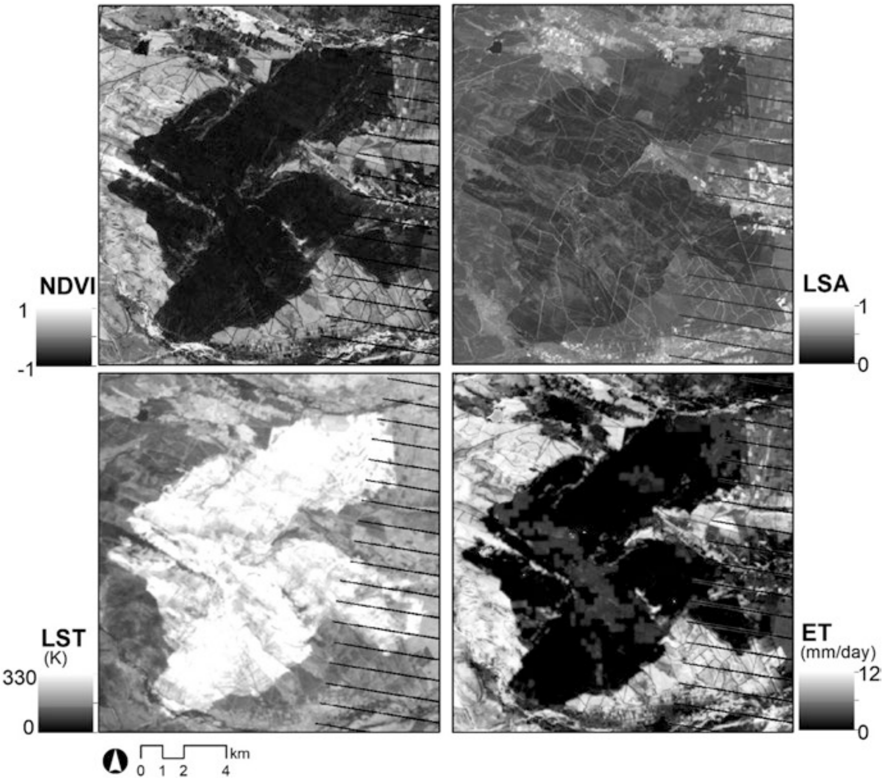


**Fig. 27.6** Representation of the normalized difference vegetation index (NDVI), evapotranspiration (ET), land surface temperature (LST), and land surface albedo (LSA) for the Castrocontrigo fire. (León, Spain) from a Landsat 7 ETM+ acquired on 6 September 2012

levels of burn severity using the normalized difference vegetation index (NDVI) as a reference (see Fig. 27.6).

Burn severity mapping is not limited to optical sensors. Amongst other applications in forestry management, LiDAR sensors are extremely useful for assessing burn severity. They provide metrics for pre- and post-fire vegetation structure, which is modified to different degrees depending on burn severity. The combination of LiDAR and multispectral satellite data for burn severity assessment is an ongoing research topic. Recently, a maximum entropy model trained with EO-1 Hyperion MESMA fraction images and LiDAR-derived vegetation structure metrics was proposed to assess burn severity (Fernández-Manso et al. 2019). The data were acquired in Valencia (Spain) in a forest dominated by Aleppo pine. The obtained model has good performance as the area under curve (AUC) values proved (AUC values >0.85).

To date, the development of new remote sensing techniques has allowed more accurate estimation of burn severity and evaluation of the effect of fuel conditions on fire severity (García-Llamas et al. 2019a). However, a suitable methodology for estimating soil burn severity in large fires has yet to be proposed. For example, spectral indices (reflective, thermal and mixed) derived from Landsat 8 OLI/TIRS used to estimate burn severity in *Pinus* forests along the Mediterranean-Transition-Oceanic climatic gradient, showed a greater ability to determine ecosystem and vegetation burn severity than soil burn severity (Fernández-García et al. 2018b) and differences in index performance among the climatic regions. The use of hyperspectral imagery shows more potential for determining changes in soil properties after wildfire, particularly with respect to the carbon stock (Peón et al. 2017). However, the results must be validated with soil samples analyzed in a laboratory. For this reason, the use of field data combined with remote sensed assessments is essential for measuring and understanding the effects of fire in forest ecosystems (Cardil et al. 2019) and transferring this information to managers.

Field burn severity assessment can be carried out by means of visual indicators or indices, which generally reflect changes in vegetation, forest floor and mineral soil. One of the most commonly used is the CBI index (Key and Benson 2006), which was developed as an operational methodology for burn severity assessment and is well-adapted to estimating burn severity variations in forests. However, this index must be modified for use in different forest ecosystems since burn severity depends on soil and vegetation, among other factors. First of all, it is important to know whether the CBI index reflects the real impact on the ecosystem after a wildfire. Both Marcos et al. (2018) and Fernández-García et al. (2019c) reported a good match between changes in soil properties (biological, chemical and physical) and the CBI index in Mediterranean pine forests (Fig. 27.7).

Similarly, the understory CBI shows a high capacity to predict microbial community response to fire (Whitman et al. 2019). This approach would make it possible to better understand relationships between remote sensing techniques and field measurements of severity. For this reason, when working with CBI, it is necessary to select indicators that reflect changes in soil and vegetation, such as char depth, litter consumption or foliage consumption (Marcos et al. 2018; Fernández-García et al. 2019c) more accurately. From a management point of view, the immediate identification of fire-induced changes in soil properties that may result in an unacceptable risk to human safety or natural resources must be a priority objective immediately after fire, to facilitate formulation of post-fire management plans.


**Fig. 27.7** Examples of soils affected by different soil burn severity values in Composite Burn Index (CBI) units: (**a**) Low soil burn severity (CBI 0.90) with blackened litter and no changes in mineral soil); (**b**) Moderate soil burn severity (CBI 2.15) with light fuel consumption, where charred remains are not completely recognizable; (**c**) High soil burn severity (CBI 3.00) where all ash is white and the soil has completely reddened

## 27.3 Remote Sensing Techniques for Monitoring Post-Fire Mediterranean Pine Regeneration

Post-fire regeneration is a heterogeneous process that varies spatially depending on fire regime parameters, pre-fire species composition, and environmental factors such as edaphic or climatic parameters (Taboada et al. 2017; Fernández-García et al. 2019b). In Mediterranean fire-prone pine forests affected by large fires, the assessment of local variations in both understory and forest canopy recovery has substantial implications for defining priority areas for management actions (Ruíz-Gallardo et al. 2004). Since the field-based monitoring of vegetation recovery in large burnt areas might be unfeasible in terms of data collection, forest managers require new tools aimed at collecting data efficiently while minimizing costs. In this sense, remote sensing techniques facilitate collection of environmental data at different spatial and spectral resolutions over large areas with little effort. The combination of this information with field data in spatially explicit modeling approaches has become an essential tool for assessing vegetation recovery at the landscape scale (Fernández-Guisuraga et al. 2019).

In recent decades, post-fire vegetation recovery in forest landscapes dominated by *P.* and *P. halepenis* has been successfully evaluated under different fire-regime scenarios of recurrence and severity using temporal series of satellite imagery collected at medium spatial resolution, such as Landsat MSS, TM, ETM+ or OLI (Díaz-Delgado et al. 2003; Viana-Soto et al. 2017). In this approach, the most frequently applied methodologies have been: (i) Time Series Analysis based on spectral indices, such as NDVI (Vicente-Serrano et al. 2011); and, (ii) Spectral Mixture Analysis (Fernández-Manso et al. 2016). Currently, a main challenge in fire ecology is to transfer these approaches to high and ultrahigh resolution time series of satellite data in order to evaluate post-fire regeneration in spatially heterogeneous landscapes (Hirschmugl et al. 2017).

High spatial resolution satellite imagery, such as that provided by Deimos-2, GeoEye-2, QuickBird or WorldView-2 on-board sensors, offers the possibility for detailed assessment of post-fire regeneration in terms of fractional vegetation cover, species richness or basal area of tree species, among other parameters. For instance, Fernández-Guisuraga et al. (2019) demonstrated in a pine forest landscape affected by a megafire in 2012 (León province, northwest of Spain) that spectral indices and textural information derived from WorldView-2 provided highly valuable information on post-fire structure of both the *P. pinaster* population (number and cover of pine seedlings) and the understory community (cover, height and richness of woody species, percentage of bare soil, necromass and leaves) that can be used as a basis for post-fire management. Indeed, WorldView-2 imagery facilitates evaluation of adaptive strategies of regeneration in the understory woody species; the fact that resprouters are the functional group of species demonstrating the highest cover and habitat suitability at high fire recurrence has implications for landscape dynamics.

Despite the general success of this approach, high resolution satellite imagery may have limited applicability in particularly heterogeneous and dynamic areas. In

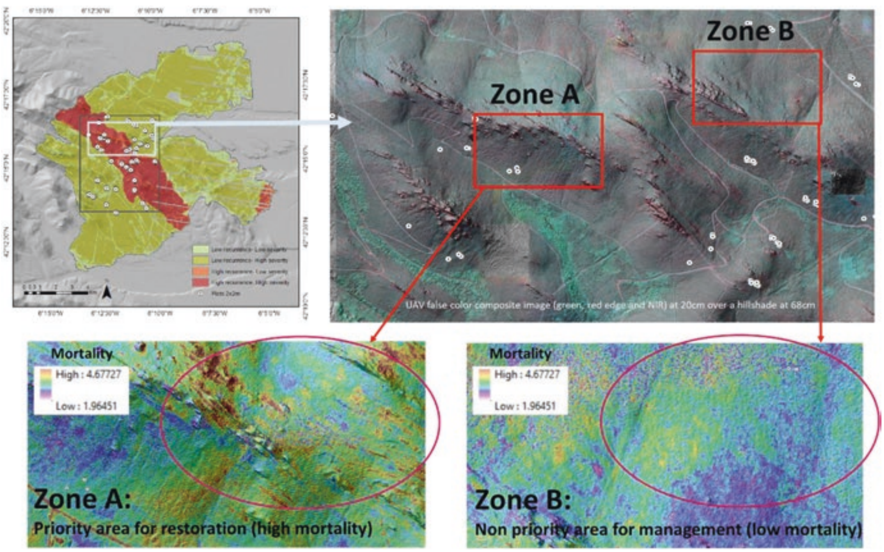


**Fig. 27.8** Priority areas for restoration identified in Castrocontrigo (León, Spain) from a pine mortality model based on multspectral drone imagery at ultra-high spatial resolution

such a case, the use of unmanned aerial vehicles (UAVs) confers advantages such as the achievement of ultra-high spatial resolution (better than 20 cm) imagery on demand. In fact, Fernández-Guisuraga et al. (2018) found that multispectral orthomosaics collected by drones provided more information in terms of spatial variability than WorldView-2 satellite imagery, becoming a potential alternative for evaluating post-fire regeneration in highly heterogeneous burned areas dominated by *P. pinaster*. Furthermore, the combination of multispectral drone imagery with population data (pine mortality rates) of the dominant tree species in mechanistic/correlative models offers a suitable framework for landscape decision-makers, since it allows detection of vulnerable zones requiring restoration across large and heterogenous, disturbed areas, as well as the landscape structures supporting population recovery (Fig. 27.8).

## 27.4 Conclusions: Wildfire Risk Management for the Reduction of Fire Damage in Mediterranean Pine Forests

Remote sensing plays a fundamental role in risk assessment – accurately predicting the occurrence of forest fires and measuring their impacts on people and ecosystem goods and services (Vaillant et al. 2016). Risk is a function of threat and vulnerability. Vulnerability is limited by the exposure, sensitivity and adaptability of a system

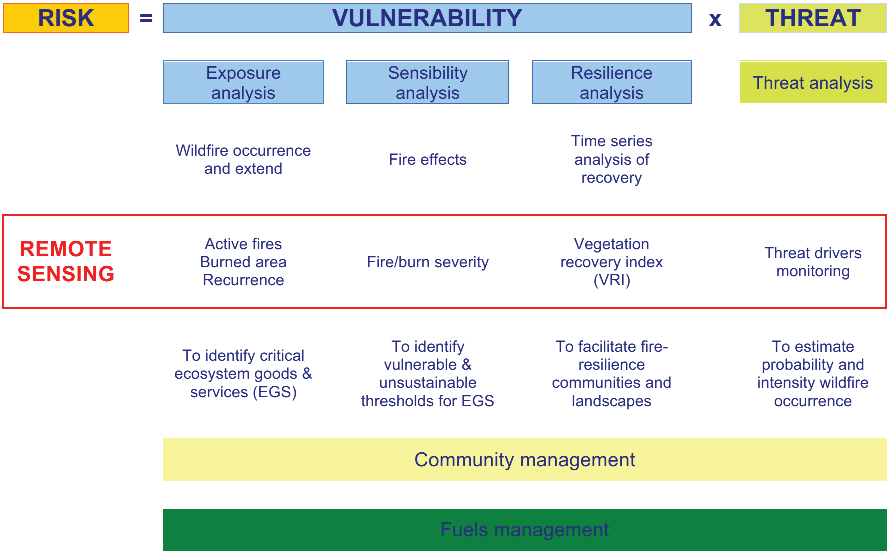


**Fig. 27.9** Risk is a function of threat and vulnerability. Reducing risk involves managing community and fuels

(resilience). Risk management requires that the threat and/or vulnerability be addressed. In all these tasks, remote sensing is presented as a powerful tool (Fig. 27.9).

Analysis of forest fire occurrence and extent is essential in the study of vulnerability. Remote sensing offers spatially continuous detection and observation of fires with daily temporal resolution. A database (whose spatial and temporal resolution depends on the used sensor) of fire occurrence and extent can be created using these data (Schroeder et al. 2014). In this sense it is of vital importance to historically analyze the attributes of the fire regime in Mediterranean ecosystems (Fernández-García et al. 2018a).

Landscape sensitivity can be quantified in terms of the effects of forest fire on key ecosystem goods and services. The focal point of sensitivity quantification is to develop burn severity databases. A thorough assessment of ecological change after fires is the key to understanding, predicting and measuring fire effects. The study of burn severity in Mediterranean pine forests using remote sensing data and techniques has produced very accurate estimates at different spatial resolutions (Fernández-Manso et al. 2016).

In Mediterranean landscapes where forest fires are a stressful factor, it is essential to analyze ecosystem resilience. Remote sensing techniques have enabled the development of vegetation recovery rates (VRI). VRI time series trend modeling provides predictions of post-fire resilience of fire-affected vegetation cover for each level of burn severity. Fernández-Manso et al. (2016) have successfully developed a VRI for *P.* in this field.

From a fire risk management point of view, remote sensing based studies such as those by García-Llamas et al. (2019a, b) have identified the main drivers of burn severity in the Mediterranean Basin and provided indications on how it can be reduced. Efficient post-fire management strategies can be proposed based on these studies (for instance, modification of fuel structure or actions aimed at the community). In all these tasks, remote sensing is an essential tool for defining optimal forest management strategies in these systems to reduce fire damage.

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