Chapter

Natural Disturbances and Protection Forests: At the Cutting Edge of Remote Sensing Technologies for the Rapid Assessment of Protective Effects against Rockfall

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Abstract

Protection forests can be severely affected by natural disturbances, whose consequences could greatly alter the fundamental ecosystem services they are providing. Assessing and monitoring the status of the protective effects, particularly within disturbed stands, is therefore of vital importance, with timing being a critical issue. Remote sensing technologies (e.g., satellite imagery, LiDAR, UAV) are widely available nowadays and can be effectively applied to quantify and monitor the protective effects of Alpine forests. This is especially important after abrupt changes in forest cover and structure following the occurrence of a disturbance event. In this contribution, we present a brief introduction on remote sensing technologies and their potential contribution to protection forest management, followed by two case studies. In particular, we focus on research areas within protection forests against rockfall affected by windthrow (i.e., the 2018 storm Vaia in the Eastern Italian Alps, where LiDAR and UAV data were used), and forest fires (i.e., the 2017 fall fires in the Western Italian Alps, involving Sentinel-2 image analyses).

Keywords: protection forests, remote sensing, natural disturbances, rockfall, forest fires

1. Introduction

In Alpine regions, forests that directly protect human assets (i.e., houses, roads, touristic and sport facilities, etc.) against rockfall cover an area of more than 20,000 km^2 (www.rockthealps.eu). These stands are defined as direct object protection forests (see chapter [1] of this book) and are providing a valuable ecosystem service to the Alpine communities. To perform an effective protection, protection forests should have specific characteristics. These include stand density and average tree size, which could be effective against different natural hazards [2], particularly gravity-driven ones (see chapter [3] of this book). Indeed, forests can provide both an active protection, avoiding the occurrence of natural hazards (e.g., impeding avalanche release), and a passive one, mitigating their impacts (i.e., in the case of rockfall), depending on their position along the slope [4].

The ability to offer a protective effect is not a permanent characteristic of a stand. Throughout their development, forests can be subject to a variety of perturbations, potentially resulting in modifications of their structural attributes that could change their protective effect. Natural disturbances, i.e., discrete events in time that disrupt ecosystem, community, or population structure and change resources, substrate availability, or the physical environment [5], can severely impact protection forests. Avalanches, forest fires, windstorms and landslides are some of the most common disturbances in mountain forests in the Alps, whose effects can profoundly influence stand dynamics.

Natural disturbances are globally expected to increase in frequency, severity, and extent due to both climate change and land use change [6, 7]. These possible alterations in disturbance regimes could result in massive modifications of the structure and composition of protection forests, with potential negative implications on the ecosystem services they are currently providing [8, 9].

Adopting appropriate forest management allows maintaining the ideal protection profile of forest stands and sustaining their protective effect [10]. Silvicultural management can also contribute to mitigating the impact of some types of disturbances, particularly those that have a lower intensity. To guide forest management in this framework, it is necessary to identify protection forests, assess their protective effect and promptly detect any alteration in its efficacy. Available field data are generally not sufficient to properly evaluate the protective effect of forests over large areas, and the costs of specific surveys are usually not sustainable [11]. Furthermore, following the occurrence of a disturbance, an early assessment of the status of protection forests and their residual protective role is fundamental.

Remote sensing tools can provide sound solutions for detecting both abrupt and gradual changes in forest stands. These tools are a valid and well-established source of data for evaluating earth surface characteristics. Active sensors (e.g., laser scanner, radar) can provide useful 3D information on forest structures and are able to extract tree size and spatial arrangement [12], while passive sensors can be used to infer vegetation status and forest cover [13]. For example, active Synthetic Aperture Radar (SAR) sensors emit a polarized signal at wavelengths in the microwave range of the electromagnetic spectrum and record the backscattered intensity at different polarizations. Depending on the emitted wavelength, the local incidence angle and other factors, the backscatter behaves differently according to land-cover type, texture and even vegetation biomass. This allows detecting specific types of land-cover and changes that occur over time. The advantage of active technologies is that they are largely independent from lighting and atmospheric conditions.

In contrast, passive sensors collect light from the sun that is reflected from the Earth surface. Spectral signatures from surface objects are created by sampling reflected light at sensor-specific wavelengths. These spectral signatures can be analyzed through transforming the spectral components (e.g., vegetation indices) and via classification and regression methods, also using modern artificial intelligence approaches (e.g., neural networks, random forest).

Integrating data from active and passive sensors can provide complementary information related to forest attributes, ranging from biomass [14] to structural parameters and canopy characteristics [15]. The European Copernicus programme manages Sentinel 1 and Sentinel 2 missions that respectively provide active and

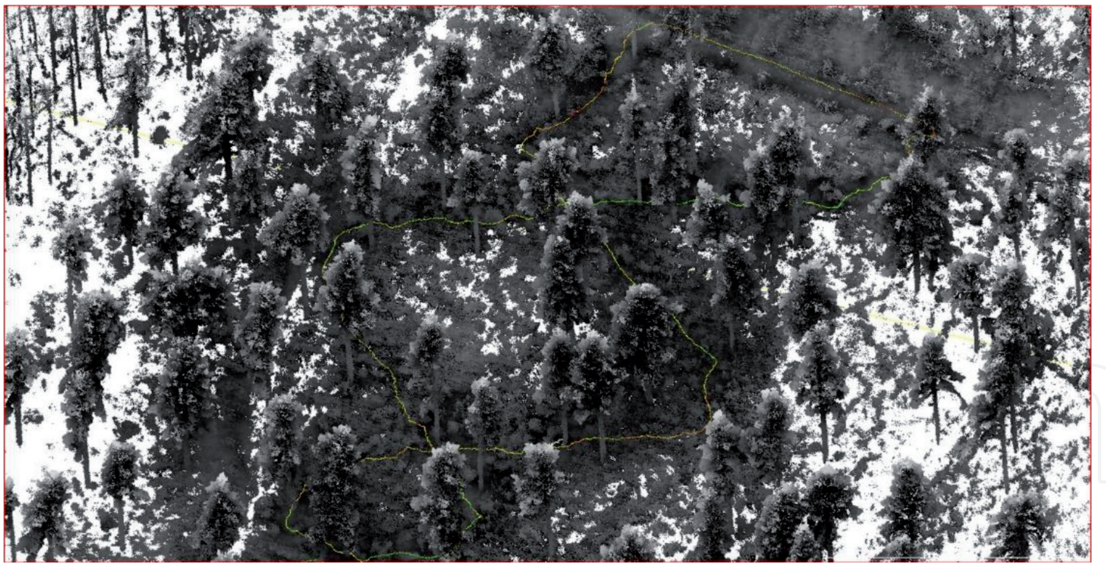

Figure 1.
Point cloud generated by a mobile mapping platform for rapid mobile scanning (Kaarta stencil 2) in the Mompantero site (Susa Valley, Piemonte, Italy) after the 2017 Susa fire.

passive remote sensing data at up to 10 m resolution. They were launched in 2014 and 2015, respectively, and have a revisit time of a few days. The Copernicus services offer unprecedented temporal and spatial coverage over forest stands, allowing an accurate assessment of the effects of disturbances and their impacts on forest ecosystem services.

At the forest stand scale, it is now possible to apply new technologies for fast data acquisition. Portable or handheld LiDAR is an innovative solution that can prove very effective since it allows to acquire data (i.e., point clouds) by simply walking in the forest (**Figure 1**). The sensor can be installed onto a hand-held system or can be carried in a backpack. This system works by emitting a laser beam, collecting the distance between the sensor and object, as well as beam angles and thus generating a point cloud. By coupling a digital camera, the point cloud generation can be enhanced since the color information helps the point matching. The registration of the point clouds is usually made adopting the Simultaneous Localization and Mapping approach, using several computer vision algorithms [16, 17].

Unmanned Aerial Vehicles (UAV) [18–20], both multirotor and fixed wings, can be employed to collect data, using different types of sensors. Nowadays, it is possible to install daylight, near infrared, multi/hyper-spectral, and thermal cameras, as well as a laser scanner on a drone. These autonomously flying systems allow collecting data very rapidly and with a very high spatial resolution. Photogrammetric processing of the UAV imagery allows generating orthophotos with different radiometric information and point clouds for digital surface and elevation models.

In the following, we describe two case studies where active sensors at the stand scale and remote sensing products from passive sensors were applied to assess the status of protection forests following high-severity forest disturbances.

2. Assessing the protective effects of forests after high-severity disturbances

The most frequent abiotic disturbances within European forests are windthrow and forest fires. In recent years unprecedented events affected mountain stands, posing serious threats to their ability to provide fundamental ecosystem services (e.g., protection against natural hazards) and creating a series of issues to be solved by their post-disturbance management. Remote sensing applications were tested to assist in the different phases of emergency management.

2.1 The 2018 windthrow events in the Dolomites due to the the storm Vaia (eastern Italian Alps)

At the end of October 2018, the storm Vaia affected the Central and Eastern Italian Alps, damaging more than 42,000 ha of forests with different levels of severity [21]. The windthrown forests were mostly located in steep terrain or in the valley bottom, where the wind was funneled. The majority of the stands on the slopes were protection forests. Salvage logging operations started right after the event and are still ongoing. However, in those areas where the potential for new avalanche releases in the absence of the forest cover was detected, it was decided to leave all the windthrown material on the ground until permanent or temporary technical protection structures are built. Research conducted in Switzerland after the storm Vivian in 1990 demonstrated that the presence of deadwood could have a positive effect in dissipating the energy of falling blocks [22, 23], by increasing the terrain roughness. However, an exhaustive quantification of this effect and its duration in relation to wood decay dynamics is still missing [24, 25]. Furthermore, leaving deadwood on-site can maintain a higher level of biodiversity [26] and enhance regeneration establishment. To incorporate the friction value provided by windthrown material into natural hazard simulation models, roughness estimation should be performed right after the events to assess the post-disturbance conditions. The spatialization of roughness data assessed through field surveys is quite complex. The spatial arrangement of deadwood elements on the ground affects rockfall in different ways: a continuous layer can for instance maximize rock energy dissipation, while tall clumps can result in a highly effective barrier for larger blocks. In the past this issue was solved by assigning the same value measured on a point location in the field to a homogeneous polygon (e.g., forest management unit, forest cover category). Recent remote sensing techniques allow performing a refined spatialization by providing spatially continuous data. Roughness information, relating to both standing and lying deadwood, can be obtained through LiDAR data. This approach has only recently been applied but has already proven to be effective in providing useful insights into the heterogeneity of the spatial arrangement of elements [27]. The availability of more spatially refined data on this feature improves simulation accuracy.

In the municipality of Colle S. Lucia (BL, Italy), in the framework of the RockTheAlps project (ASP462), the efficiency of a rockfall protection forest has been assessed in 2018, before the storm occurred. This was achieved by adopting a combined remote sensing and field data collection methodology (**Figure 2**). LiDAR data acquired in 2015 combined with a UAV data acquisition in July 2018 were used to extract single tree positions on the slopes.

The protective effect has been assessed using Rockyfor3D (v 5.2; [28]), running 1,000 simulations with a rock size corresponding to the 95th percentile of the rock deposits observed in the field (1.5 x 1.0 x 0.8 m, corresponding to 1.2 m^3). Stand data were validated within field plots where other parameters needed for the rockfall simulations were also recorded. Based on the software outputs, the Overall Rockfall Protection Index (ORPI; [29]) was computed for three different positions on the slope: the state road at the bottom, the municipality road to the Colcuc village in the middle, and a severely affected section (checkpoints 1, 2, and 3, respectively, in **Figure 3**). This index describes and quantifies the protective effect against rockfall by integrating the proportion of stopped rocks (frequency) and the total rock energy reduction due to forest cover (intensity) [29].

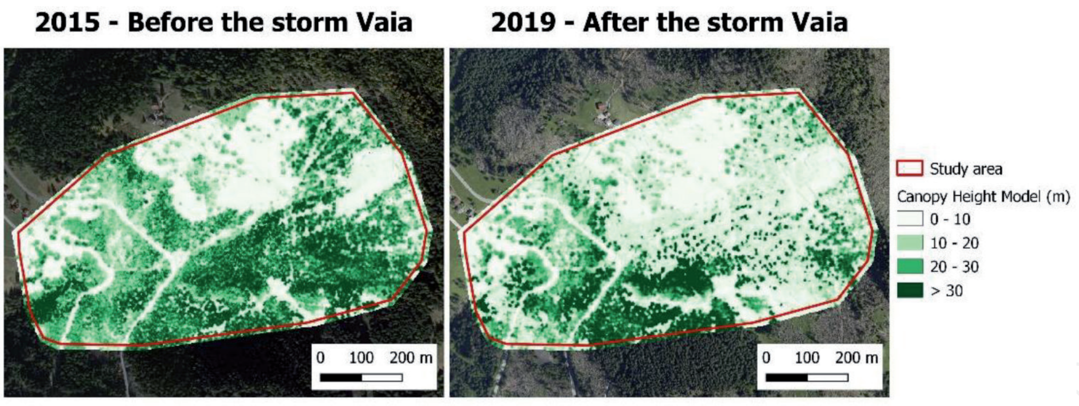

Figure 2.
Canopy height models (CHMs) derived from LiDAR data before (left; 2015) and after (right; 2019) the storm Vaia in the Colcuc case study (Colle S. Lucia, BL, Italy).

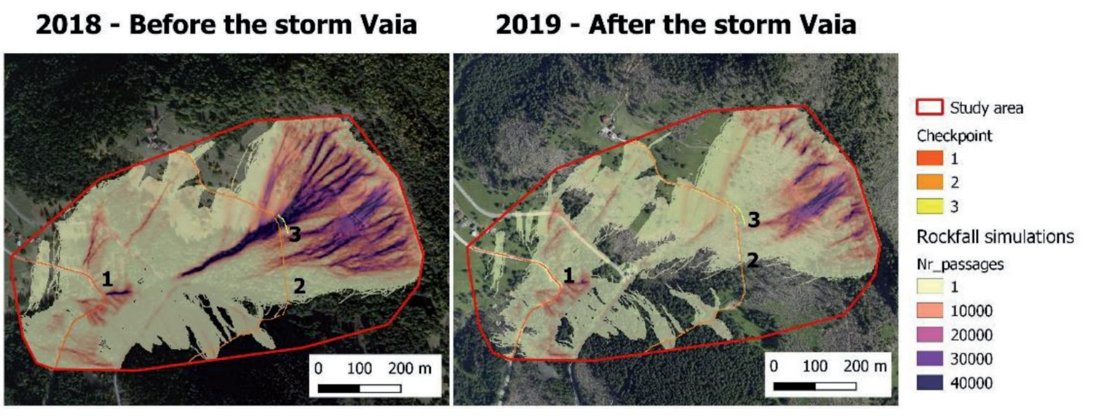

Figure 3.
Rockfall simulation with RockyFor3D in two scenarios: Before (left; 2018) and after (right; 2019) the storm Vaia in the Colcuc case study (Colle S. Lucia, BL, Italy). Maps show the cumulative number of rock passages meaning the number of rocks going through a cell based on 1,000 simulations (i.e., number of rocks released per source cells). Checkpoints are specific locations on the ground (the state road at the bottom, the municipality road to the Colcuc village in the middle, and a severely affected section: Checkpoints 1, 2, and 3, respectively), where the ORPI [29] was calculated.

Later that year, the storm Vaia hit the site, leaving a large amount of timber on the ground. In July 2019, new LiDAR data and aerial imagery were acquired, providing up-to-date information on the forest status after the event. A new set of simulations was then performed using the forest cover values resulting from the windthrow and new roughness values for the windthrown area, to take into account the obstacles provided by logs and uprooted stumps. This information has been directly extracted from the LiDAR scans adopting an approach that makes use of quantiles of point distribution on a height-normalized point cloud filtered for the first returns [30].

All the other input parameters have been maintained (i.e., rock characteristics, number of simulations, etc.) to consider the same rockfall scenario and compare results before and after the disturbance. Post-disturbance simulations highlighted a peculiar situation since the protective effect, at least in the short term, was even improved along the slope after Vaia. In each analyzed checkpoint, the ORPI value actually increased (**Figure 4**), in most cases leading to a promotion to the upper class of protective effect (e.g., from low to medium or medium to high; for details on class thresholds see [29]), meaning that the presence of lying deadwood exerted a positive effect in increasing the protection against rockfall. The protective effect should however be assessed through time, monitoring the decay dynamics, the reduction in height above ground of downed logs, and the displacement of logs due

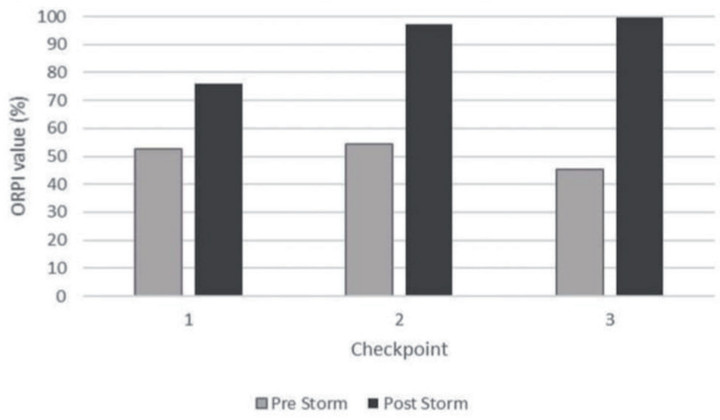

Figure 4.
The overall protection (expressed by ORPI) against rockfall provided by the forest in the Colcuc case study (Colle S. Lucia, BL, Italy) above the three checkpoints before and right after the storm Vaia (see ***Figure 2*** *for checkpoint locations).*

to downslope movements [31] and snow pressure. Remote sensing techniques such as LiDAR or UAV will continue to provide useful quantitative information about these dynamics.

2.2 The 2017 large forest fires in the Piedmont region (Western Italian Alps)

The severe and prolonged summer drought, which occurred in South-Central Europe in 2017 [32] was a major predisposing factor for the simultaneous ignition and spread of several forest fires in the Piedmont Region of Italy during the second half of October. These fires affected nearly 10,000 ha, including more than 7,200 ha of forest stands. Given the importance of fire severity in determining post-fire recovery dynamics, its assessment was considered a key issue to guide post-disturbance management and particularly to identify priority areas where to first intervene. The extensive areas affected by the fires made the application of remote sensing techniques highly useful and different severity indices, commonly applied in other regions of the world, were tested at these sites.

Fire severity maps were produced for the 10 largest forest fires (extent > 50 ha) by adopting the approach formerly developed within the Fire Effects Monitoring and Inventory System [33], which is aimed at integrating optical satellite data and field data (**Figure 5**). A multitemporal analysis based on multispectral imagery acquired by Sentinel-2 was employed to map spectral changes induced by fire in the near infrared and the shortwave infrared wavelengths using indices that compare pre- and post-fire conditions based on the Normalized Burn Ratio (NBR): the differenced NBR [33], the Relative difference NBR [34], and the Relativized Burn Ratio [35]. Field data collected using the Composite Burn Index protocol (**Figure 6**) were employed to obtain independent severity ratings, to be used to calibrate and validate remote sensing results, relating detected radiometric change to actual fire effects on the ground (**Figure 7**) [33]. The Composite Burn Index is obtained within plots (in our case 20 m circular plots) by ocularly evaluating the degree of change induced by fire in five vegetative strata, from the substrates to the dominant trees. Different attributes per stratum are rated on a burn severity scale, ranging from 0.0 (no burn effect) to 3.0 (highest burn effect). Stratum, understory, overstory, and overall composite ratings are then obtained by adding up scores within each hierarchical level and dividing by the number of rated factors. The overall index represents the magnitude of fire effects combined across all strata. In particular, the relationship between the overall Composite Burn Index score assessed in 251 plots

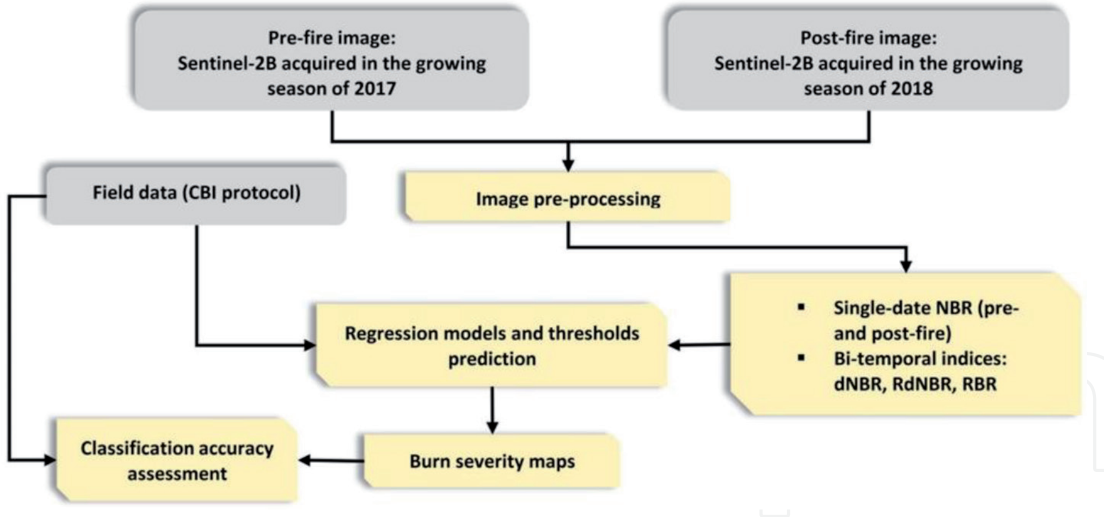

Figure 5.
Developed workflow to retrieve burn severity maps from remote sensing data based on remote sensing indices (normalized burn ratio, NBR; differenced normalized burn ratio, dNBR; relative difference normalized burn ratio, RdNBR; relativized burn ratio, RBR) and field data (composite burn index, CBI).

Figure 6.
*Patches burned at different severity in protection forest stands dominated by scots pine (*Pinus sylvestris *L.) and European larch (*Larix decidua *mill.), and corresponding composite burn index (CBI) values. CBI quantifies the degree of change induced by fire thorough ocular evaluation of different attributes in five vegetative strata within field plots, along a burn severity scale, ranging from 0.0 (no burn effect) to 3.0 (highest burn effect). The overall CBI value for a plot is obtained by averaging attribute scores for all strata and used to describe fire severity. This index can then be related to the normalized burn ratio index (and other bi-temporal indices based on the normalized burn ratio index), obtained through remote sensing data.*

and each bi-temporal index was evaluated through nonlinear regression models, which subsequently provided a threshold for classifying bi-temporal indices into burn severity categories.

The adopted methodology provided satisfying overall classification accuracies of severity maps, ranging from 77.7% to 79.3% depending on the bi-temporal index. Stands dominated by conifers, i.e., Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua* Mill.), were burned by stand replacing crown fires, killing both the canopy trees and the understory (i.e. regeneration, shrubs), deeply affecting the soil organic layers and potentially compromising the protective effect for a long period of time. In contrast, broadleaf-dominated stands (e.g., European chestnut [*Castanea sativa* Mill.] and European beech [*Fagus sylvatica* L.]) were mainly burned by low and moderate severity fires [36], that affected only the understory layers, without major changes in the potential protective effect of the forest.

Overlapping the severity maps with the layers of protection forests against rockfall and the historical avalanche sites, priority areas were identified and mapped. Those stands characterized by high fire severity (namely those experiencing stand replacing crown fires) and a relevant protective function, whose protective effect

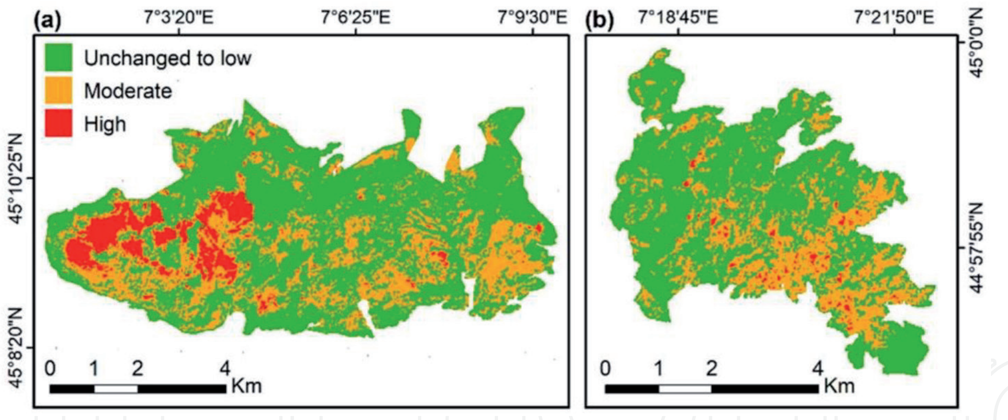

Figure 7.
Burn severity maps derived from the relative difference normalized burn ratio (RdNBR) index for (a) the Susa fire and (b) the Cumiana fire (Piemonte, Italy).

had thus potentially been highly compromised, were selected to perform interventions devoted to the rapid recovery of the protective effect, adopting ecoengineering techniques (building wooden structures with burned logs) and afforestation.

3. Conclusions

The availability to collect timely information on the status of protection forests is of fundamental importance for their management, particularly in the aftermath of high-severity disturbances, both in the response and recovery phases. Currently several freely available data sources are accessible to forest and land managers, as well as new tools and software (**Table 1**), to increase the amount of and improve information required to support a sustainable forest management in the framework of global change challenges. Rapid mapping through remote sensing technologies operating over large areas allows monitoring and updating on-demand knowledge about the protective effect of a stand, providing key data to guide the decision-making process. Characterizing disturbance severity and relating its short- and long-term effects to the stand residual protective effect can have a direct applicability in forest management to spatially define intervention necessities and priorities.

The described methodologies and related technologies are currently operational and require medium level skills in using GIS and remote sensing tools. Concerning LiDAR, some pre-processed data (e.g., Canopy Height Models) are more and more available for end-users, but directly managing the point clouds still remains a task restricted to more skilled experts. Given the rapid progress in the development of new remote sensing technologies and tools for describing, measuring and monitoring forest stands, the forest sector as a whole should invest in training and continuing education in this field to keep its members updated to be competitive in rapidly evolving scenarios.

Category	Details	Website
Multispectral satellite data at medium spatial resolution	Landsat missions (Landsat 4–5 TM; Landsat 7 ETM+; Landsat 8 OLI/TIRS)	https://earthexplorer.usgs.gov/
	Sentinel-2 mission (Sentinel-2A and 2B)	https://scihub.copernicus.eu/

Category	Details	Website
Open-source software for remote sensing data analysis	FORCE: Framework for Operational Radiometric Correction for Environmental monitoring	https://github.com/davidfrantz/force
	R "raster" package	https://cran.r-project.org/web/packages/raster/index.html
	R "terra" package	https://github.com/rspatial/terra
	R "RStoolbox" package	http://bleutner.github.io/RStoolbox/
	Orfeo Toolbox	https://www.orfeo-toolbox.org/
	SAGA GIS	http://www.saga-gis.org/
	FUSION/LDV	http://forsys.cfr.washington.edu/fusion/fusionlatest.html
	R "Forest Tools" package	https://github.com/andrew-plowright/ForestTools
Free-of-charge cloud-computing platforms for remote sensing data analysis	Google Earth Engine	https://earthengine.google.com/
	Copernicus Research and User Support	https://rus-copernicus.eu/portal/the-rus-service/

Table 1.
Examples of freely available data, open-source software, and free-of-charge cloud-computing platforms for remote sensing data analysis (the list in the table is non-exhaustive).

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Conflict of interest

The authors declare no conflict of interest.

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