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RESEARCH PAPER

Assessment of a wildfire in the remaining *Nothofagus alessandrii* forests, an endangered species of Chile, based on satellite Sentinel-2 images

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Abstract

R. Santelices-Moya, A. Cabrera-Ariza, P. Silva-Flores, and R.M. Navarro-Cerrillo. 2022. Assessment of a wildfire in the remaining *Nothofagus alessandrii* forests, an endangered species of Chile, based on satellite Sentinel-2 images. Int. J. Agric. Nat. Resour. 85-96. *Nothofagus alessandrii* is an endangered species that is naturally distributed in a Mediterranean environment in central Chile. In recent years, this territory has been subject to the effects of climate change, especially an increase in summer temperatures and prolonged periods of drought. In the summer of 2017, there was a fire of great magnitude consuming 184,000 ha, which affected the forests of *N. alessandrii*. This study assessed the severity and recovery dynamics of postfire vegetation by using spectral indices from Sentinel-2 images. The differenced normalized burn ratio (dNBR), relative differenced normalized burn ratio (RdNBR), and relativized burn ratio (RBR) were calculated before and after the fire and, later, the normalized difference vegetation index (NDVI) before the fire and during three consecutive years after the fire was utilized. The accuracy of the fire severity classifications was estimated using the kappa test ($p<0.05$). The three severity indices showed a similar classification in severity assessment and postfire response. The low-medium burn area in *N. alessandrii* forests ranged between 111.2 ha (RdNBR) and 130.3 ha (dNBR), and the high effect was between 46.1 ha (dNBR) and 66.0 ha (RdNBR), which was equivalent in both cases, approximately 11% of the total. Regarding the NDVI, vegetation recovery after three years of the fire showed a systematic return to prefire conditions. The assessment of the effect of a mega forest fire on the remaining forests of *N. alessandrii* based on Sentinel-2 images offers the opportunity for a better understanding of the severity of damage and the behavior of vegetation after the fire. All this information will help in a better recovery of these forests.

Keywords: Mediterranean forest, postfire restoration, remote sensing, ruil, spectral indices.

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Introduction

The Mediterranean zone of Chile is characterized by a great diversity of endemic species and is considered a "hotspot" of biodiversity for conservation, although this has decreased to critical levels in terms of dominance and variability, mainly due to anthropogenic factors (Myers et al., 2000). This area is characterized by the presence of deciduous forests that are adapted to prolonged dry summers and play a very important role in the conservation of water and organic soil, in the biogeochemical cycle of carbon, and offer a variety of ecological niches and habitats to flora, fauna and associated microbiota (Arroyo et al., 1996). The highest human population density in Chile is also concentrated in this area, causing a strong pressure on natural resources. One result has been the sharp decline in natural forests in this region (Donoso & Lara, 1996). This forest degradation can be illustrated by *Nothofagus alessandrii* Espinosa (Nothofagaceae) (Ruil), an endemic and endangered species in central Chile (Barstow et al., 2017) and one of the representative species of the Mediterranean *Nothofagus* forests of South America. The forest degradation of relict stands of *N. alessandrii* is probably one of the clearest examples of environmental deterioration resulting from anthropogenic actions in Chile.

The situation in which the remaining forests of this species are found is critical. They are only located in the Cordillera de la Costa of Chile, in a latitudinal extent that does not exceed 100 km, having a discontinuous and highly fragmented distribution, reaching a total estimated area of 314 ha before the 2017 fire (Santelices et al., 2012). The expansion of plantations with fast-growing species has resulted in the invasion of exotic species such as *Pinus radiata* D. Don in *N. alessandrii* forests (Bustamante & Castor, 1998; San Martín et al., 2013). The loss of *N. alessandrii* forests between 1991 and 2008 was quantified to be 42 ha, which represents an annual deforestation rate of 0.74% (Santelices et al., 2012). Another threat that is highly impacting *N. alessandrii* forests is global climate change (Santelices et al., 2018). Due to the increase in prolonged periods of drought and high temperature, the probability of occurrence of forest fires increases over time. In fact, during the summer of 2017, the largest number of fires were recorded in the Mediterranean zone of Chile (de la Barrera et al., 2018). One of them covered 184,000 hectares, affecting different agricultural and forestry systems, among them an important part of the remains of *N. alessandrii* forests (Valencia et al., 2018).

In the event of a disturbance event, such as a wildfire, it is necessary to take measures to restore the affected systems, especially when these systems are already threatened, as is the case for *N. alessandrii* forests. The actual knowledge of the severity of a forest fire over a territory is an important support tool for postfire restoration, and the decision-making process is more effective if maps of fire severity are available (Botella-Martinez & Fernandez-Manso, 2017). In this context, remote sensing is a tool that undoubtedly facilitates restoration programs, and through the use of satellite images, using a combination of different spectra, several reliable indices can be calculated to assess fire severity (Morgan et al., 2014). The NBR index (normalized burn ratio) is a normalized spectral index that, by means of a combination of the near infrared and the medium infrared bands, allows us to evaluate fire severity by comparing the pre- and postfire index (i.e., differenced normalized burn ratio, dNBR) (Key & Benson, 2006; Veraverbeke et al., 2010). This index has been widely used in forest fire assessment (Boucher et al., 2017; Escuin et al., 2008; Key & Benson, 2006; Miller & Thode, 2007). Subsequently, other indices have been developed, among which we can mention the relative differenced normalized burn ratio (RdNBR) (Miller & Thode, 2007) and, more recently, the so-called relativized burn ratio (RBR) (Parks et al., 2014). The RdNBR was developed with the purpose of avoiding sensitivity to changes where the coverage of prefire vegetation was low (Miller et al., 2009; Miller & Thode, 2007). However, Parks et al. (2014) argued that from a mathematical point of view, there are some difficulties with the denominator of the formula in calculating this index. The transformation of the square root causes very low values of the prefire NBR, leading to low or negative differences; therefore, these authors proposed a new metric called the RBR index, as an improved alternative to quantify fire severity. The relationship between fire severity and postfire vegetation together with the threat of invasive tree species is a key aspect of restoration (García-Duro et al., 2016). Postfire vegetation recovery has been widely evaluated using the normalized difference vegetation index (NDVI) (Leon et al., 2012; Meng et al., 2015; Torres et al., 2018).

In this context, Valencia et al. (2018) estimated the severity on the *N. alessandrii* forests caused by the "Las Máquinas" fire through the use of the dNBR. However, this was a preliminary approach that did not consider field verification. The main objective of this study was to assess the effect of a mega forest fire on the remaining forests of *N. alessandrii* based on Sentinel-2 satellite images. The specific objectives were (1) to compare fire severity assessment by using the dNBR, RdNBR, and RBR indices from *N. alessandrii* forests and (2) to evaluate the initial vegetation recovery of *N. alessandrii* forests after a mega fire using the NDVI. The results will improve our understanding of *N. alessandrii* forests to develop restoration scenarios.

Materials and methods

Study area

The study area was located in the "Las Máquinas" fire area (Figure 1), which was the largest recorded fire in the Mediterranean area of Chile, covering an area of approximately 184,000 hectares of different agricultural and forest systems. This fire affected close to 55% of the *N. alessandrii* forests (Valencia et al., 2018). The climate is typically Mediterranean, with an average temperature of 13.7 °C (maximum in January 24.8 °C and minimum in July 5.9 °C). The thermal amplitude is lower than 20 °C as a consequence of the oceanic accentuated thermoregulation and cold and humid sea breeze from the northwest in the winter and from the southwest in the summer (San Martín et al., 2013). The year before the fire (2016), the average annual rainfall varied from 308 to 434 mm, with a maximum in July of 188 mm (DMC, 2017). During the summer of 2017, there was a complex scenario consisting of accumulated drought and the high fuel load available (CONAF, 2017), which led to the development of the large forest fire.

Satellite images and image processing

A Sentinel-2 scene downloaded from the European Space Agency (https://scihub.copernicus.eu/dhus/#/home) was used to estimate fire severity and vegetation vigor before and after the fire. Two images were used, taking into account the fire ignition (01.19.2017) and extinction (02.02.2017) dates, to minimize the phenological and solar angle differences (Arellano et al., 2017). Atmospheric and topographic corrections were conducted, and the influence of shadows was not considered to be decisive for a first approach to the fire area (Botella-Martinez & Fernandez-Manso, 2017). Fire cover was determined by the composition of RGB bands of the scene after the fire. The vector layer was superimposed on *N. alessandrii* forests (Santelices et al., 2012) to generate a first approximation of the area affected by the fire (Figure 1). In the assessment of vegetation recovery, only shrub and tree covers were considered, and images corresponding to the dry period (summer, January) were selected to correspond when herbaceous vegetation was already dry. The two Sentinel-2A images used in this study were downloaded at Level-1C (L1C) of processing (e.g., radiometrically and geometrically corrected Top-Of-Atmosphere-TOA, https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/product-types/level-1c). A mosaic was carried out using QGIS (v2.14.0) for each

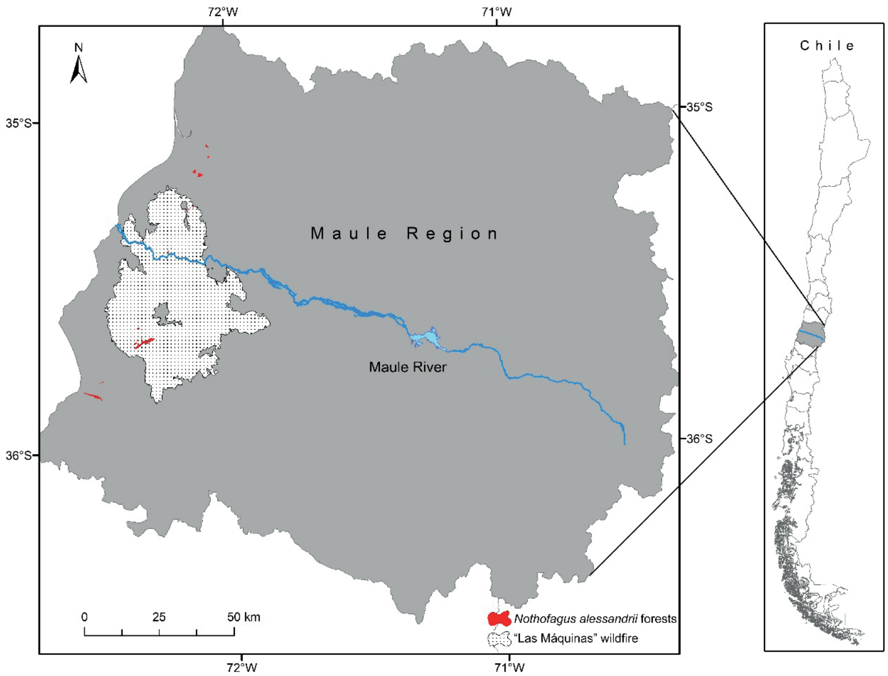

Figure 1. The area affected by a major fire that occurred in the Maule Region (Mediterranean zone of Chile), which affected the remaining forests of *Nothofagus alessandrii*.

spectral band, and noncloud coverage was observed. A satellite image was obtained before the fire (01.19.2017) and three other images after the event for three consecutive years on 01.08.2018, 01.04.2019, and 01.24.2020.

Field data

A systematic sampling was carried out, and 173 temporary sampling plots of 20 m x 20 m were established (3.6% of the study area), which were georeferenced and classified according to the damage observed. The magnitude of the damage caused by the fires was visually assessed following the indications given by Botella-Martinez and Fernandez-Manso (2017). Three damage categories were considered according to the degree of effect of the fire: a) no effect: not burned; b) low-medium effect: the canopy of the trees did not suffer damage, remaining entirely green; only the shrub canopy and part of the stem of the trees were affected; scrub appeared mostly burned, but the observed ash was predominantly black; and c) high effect: the canopy of the trees was completely consumed, leaving no leaves or fine elements; therefore, the black color predominated, the scrub was completely charred leaving only the thickest elements, and the ash predominantly had gray or whitish tones.

Assessment of fire severity and vegetation recovery

Three spectral indices were calculated: dNBR (Key & Benson, 2006), RdNBR (Miller & Thode, 2007), and RBR (Parks et al., 2014). The NBR index was calculated from the near infrared (NIR) and middle infrared (SWIR) bands, which, in the case of Sentinel-2, correspond to bands 8a (865 nm) and 12 (2 190 nm), respectively (Table 1).

Table 1. Formulas used to assess fire severity and vegetation recovery.

Formula	Reference
$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}$	Key & Benson (2006)
$dNBR = (NBR\ prefire - NBR\ postfire) * 1000$	Parks et al. (2014)
$RdNBR = \frac{dNBR}{\mid (NBR\ prefire) \mid \hat{}0.5}$	Miller & Thode (2007)
$RBR = \frac{dNBR}{NBR\ pre\ incendio + 1.001}$	Parks et al. (2014)
$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$	Meng et al. (2015)

Once the three fire severity indices were generated, they were classified into the categories indicated above: no effect, low-medium effect, and high effect. The thresholds used to establish the three categories of severity for the dNBR, RdNBR and RBR were those proposed by Key and Benson (2006), which were later adjusted according to the preliminary evaluation carried out in the field. Additionally, forest recovery was estimated using the (NDVI) values postfire, which has been widely used to discriminate postfire vegetation dynamics (Meng, 2015; Gao, 2020). A NDVI value of 0.5 was used as the lower limit.

Classification accuracy

We estimated the accuracy of the fire severity classifications by internal cross-validation using a matrix of burn severity estimates with 1/3 of the field sampling plots. Overall accuracy (OA), producer's accuracy (PA), user's accuracy (UA) and the κ statistic were calculated (Congalton & Green, 2009). A chi-squared test enabled us to check whether κ statistic differences between the two burn severity maps had statistical significance ($p<0.05$). The statistical analysis was performed using SPSS software Version 18 (SPSS, Inc., Chicago, IL, USA).

Results

Thresholds for classification of postfire severity

The operational thresholds obtained for the classification of postfire severity are shown in Table 2. The postfire severity values of the three indices are included in Table 3. The total area affected by the fire was slightly different according to the calculated index, showing an area that was not affected by the fire, which varied between 0.5% and 1%. The nonaffected area ranged from 0.8 ha (RdNBR) to 1.7 ha (dNBR). The low-medium burn area in *N. alessandrii* forests ranged between 111.2 ha (RdNBR) and 130.3 ha (dNBR), and the high effect between 46.1 ha (dNBR) and 66 ha (RdNBR) was equivalent in both cases, approximately 11% of the total.

Classification accuracy

Classification accuracy showed an overall reliability between 80% and 83%, being highest for the RdRBR index. The kappa index ranged between 0.5 and 0.6, and the highest value also corresponded to the RdRBR index (Table 4).

Table 2. Thresholds for classification of fire severity in forests of *Nothofagus alessandrii*. Normalized burn ratio (dNBR), relative differenced normalized burn ratio (RdNBR) and relativized burn ratio (RBR).

	Thresholds for classification of fire severity		
Indice	No effect	Low-medium effect	High effect
dNBR	100	660	1380
RdNBR	100	660	2683
RBR	55	350	924

Table 3. Area affected by the "Las Máquinas" fire in the forests of *Nothofagus alessandrii* according to indices and fire severity.

Location	Burn area according to indices and fire severity (ha)								
	dNBR			RdNBR			RBR		
	No effect	Low-medium effect	High effect	No effect	Low-medium effect	High effect	No effect	Low-medium effect	High effect
"Agua Buena"	0.1	1.3	0.2	-	1.2	0.2	0.1	1.2	0.2
"Bellavista"	0.5	6.9	0.1	0.2	6.8	0.3	0.4	6.9	0.2
"Coipué"	-	1.8	0.8	-	1.2	1.4	-	1.6	0.9
"El Desprecio"	-	36	3.8	-	31.7	7.9	-	33.4	6.4
"El Fin"	0.4	10.1	-	0.2	10.4	-	0.3	10.3	-
"El Porvenir"	0.7	44	1.6	0.4	42.9	3.0	0.5	43.4	2.3
"La Montaña"	-	28.8	35.4	-	15.9	48.7	-	20.4	43.9
"Quivolgo"	-	0.7	4.2	-	0.5	4.4	-	0.6	4.3
"Suc. Espinoza"	-	0.7	-	-	0.6	0.1	-	0.7	-
Total	1.7	130.3	46.1	0.8	111.2	66	1.3	118.5	58.2

Table 4. Kappa statistic values for the dNBR, RdRBR, and RBR indices for assessing fire severity in *Nothofagus alessandrii* forests affected by the "Las Máquinas" fire (Southern Chile).

Indices	Global reliability (%)	Kappa Indices
dNBR	80	0.5
RdRBR	83	0.6
RBR	80	0.5

Assessment of vegetation recovery

NDVI values showed that vegetation recovery tended to increase after the fire. Prior to the fire, the NDVI ranged from 0.6 to 0.8 (~ 88% of the surface area subsequently affected by the fire), which was considered as a baseline for assessing the recovery of the vegetation (Table 5). Three years after the fire, a tendency for vegetation recovery was observed (Tables 6).

Discussion

In Chile, forest fires are a frequent phenomenon that has shaped the landscape (Úbeda & Sarricolea, 2016). However, the occurrence of mega fires in 2017 was favored, among other factors, by weather conditions outside the normal range (Harris et al., 2016). In this study, different post-fire severity indices were compared to assess the impact of a large fire on *N. alessandrii* forests in central Chile. It was proven that these indices well reflect the severity of the fire and that they can be related to the recovery of the vegetation measured by the NDVI.

Thresholds for classification of postfire severity

The fire severity classification thresholds were established following Key and Benson (2006), using three different indices, dNBR, RdNBR and RBR. However, the RBR index was further adjusted according to the preliminary field observations, especially in those areas without fire effects. A tendency to underestimate the burned surface was observed, considering that the classification thresholds reported in other studies can be variable (Arellano et al., 2017; Botella-Martinez & Fernandez-Manso, 2017). To more effectively estimate the area affected by the fire, it is essential to carry out a preliminary evaluation to adjust the

Table 5. Area of *Nothofagus alessandrii* forests classified in different categories of normalized difference vegetation index (NDVI) before the "Las Máquinas" fire (January 2017).

Location	Normalized Difference Vegetation Index (NDVI) category			
	<0.5	0.5-0.6	0.6-0.7	>0.7
	January 2017 prefire			
"Agua Buena"	0	0	0.1	1.4
"Bellavista"	0	0.3	1.9	5.3
"Coipue"	0.6	0.2	0.4	1.3
"El Desprecio"	0.7	7.4	20.5	11.2
"El Fin"	0.1	0.6	6.1	3.8
"El Porvenir"	0.6	2.4	18.3	24.9
La Montaña	1.1	6.2	23.2	33.8
"Quivolgo"	0	0	0.5	4.4
"Sucesión Espinoza"	0	0	0.5	0.2
Total	3.1	17.1	71.5	86.3

Table 6. Area of *Nothofagus alessandrii* forests classified in different categories of the normalized difference vegetation index (NDVI) from January 2018 to January 2020 after the "Las Máquinas" fire.

Location	Normalized Difference Vegetation Index (NDVI) category											
	<0.5	0.5-0.6	0.6-0.7	>0.7	<0.5	0.5-0.6	0.6-0.7	>0.7	<0.5	0.5-0.6	0.6-0.7	>0.7
	January 2018 postfire				January 2019 postfire				January 2020 postfire			
"Agua Buena"	0.5	0.2	0.6	0.2	0.1	0.4	0.5	0.5	0.06	0.27	0.49	0.55
"Bellavista"	2.6	1.5	2.5	0.9	0.7	2.0	3.0	1.8	0.23	1.75	3.47	1.02
"Coipue"	2.3	0.1	0.1	0	0.8	1.3	0.4	0	0.15	1.08	1.07	0.07
"El Desprecio"	31.2	5.3	2.8	0.5	17.4	13.4	7.1	1.9	12.91	17.25	7.77	0.35
"El Fin"	1.1	3.3	4.8	1.4	0.6	2.5	5.2	2.3	0.29	3.53	4.88	1.21
"El Porvenir"	22.6	8.4	10.7	4.5	5.6	14.1	15.2	11.3	2.89	15.34	16.77	7.10
La Montaña	62.9	0.9	0.5	0	15.1	36.9	11.4	0.9	6.65	35.74	18.31	0.71
"Quivolgo"	4.8	0.1	0	0	0.3	2.0	2.4	0.2	0.10	1.83	2.97	0.10
"Sucesión Espinoza"	0.3	0.1	0.3	0	0	0.1	0.2	0.4	0	0.06	0.41	0.15
Total	128.3	19.9	22.3	7.5	40.6	72.7	45.4	19.3	23.28	76.86	56.12	11.26

fire severity classification thresholds, particularly in this case with the RBR index.

The RdNBR index was proposed to eliminate the influence of prefire vegetation, which would facilitate creating classifications using the same thresholds for fires that occur in similar types of vegetation, without the need to acquire data for the calibration of each fire (Miller et al., 2009; Miller & Thode, 2007). However, our results showed that the dNBR and RdNBR indices had the same response in terms of the classification thresholds in differentiating the medium and low categories. Although the threshold values of the dNBR and RdNBR separating fire severity classes are consistent with those proposed by Key and Benson (2006), other studies have proposed other values (Arellano et al., 2017; Botella-Martinez

& Fernandez-Manso, 2017). On the other hand, the thresholds obtained for the RBR index differ from those previously reported (Botella-Martinez & Fernandez-Manso, 2017; Parks et al., 2014). Therefore, in each particular situation, threshold values should be evaluated for each index and must be contrasted with field observations.

Based on these indices, the low-medium burn area in *N. alessandrii* forests ranged between 111.2 ha (RdNBR) and 130.3 ha (dNBR), and the high burn area ranged between 46.1 ha (dNBR) and 66 ha (RdNBR), which was equivalent in both cases, approximately 11% of the total. Therefore, it can be estimated that the remaining area of these forests would have been no more than 268 ha and could have even reached 248 ha. Thus, because of the fire, an area of *N. alessandrii* forests of at least 15% would have been lost. The nonaffected area ranged from 0.8 ha (RdNBR) to 1.7 ha (dNBR). In relative terms, the underestimation of the total burned area was less than 1%, which would be an indication that the three evaluated indices are effective, especially RdNBR (0.47%). In general, some sectors can be clearly distinguished in which fire severity was proportionally greater; for example, “El Desprecio”, “El Porvenir”, and “El Fin” located in the low-medium affected area.

Classification accuracy

According to Arellano et al. (2017), kappa values were within the ranges found in other studies, with the RdNBR index being the most accurate and with the highest total reliability. Considering the classification thresholds and the kappa index, the RdNBR index would be the most appropriate and reliable index for assessing fire severity from forest fires in *N. alessandrii* forests. This is consistent with that reported by Botella-Martinez and Fernandez-Manso (2017) and in fires affecting vegetation in Mediterranean areas (Ariza et al., 2019). However, this index has a similar behavior in terms of the area affected to the RBR index.

Assessment of vegetation recovery

When analyzing the temporal sequence of the NDVI on the dynamics of the vegetation affected by the studied forest fire, a tendency of recovery of the system could be observed three years after the fire. The recovery of the affected *N. alessandrii* forests was greater in those forests in which the severity was low to moderate. Undoubtedly, a greater photosynthetically active remnant foliar surface where the severity of the fire was low to moderate contributed to a faster vegetation recovery. In fact, *N. alessandrii* is a species with a great capacity for resilience and that has been able to maintain itself and survive over time thanks to the fact that it has developed survival strategies such as the ability to resprout after being affected by a disturbance (San Martín et al., 2013). Under normal conditions, good germinative potential has been observed, but later, the seedlings do not reach the juvenile stage due to physical factors, such as mechanical and eco-physiological factors, at the site (San Martín et al., 2013). However, in those places with high severity values, the vegetation recovery was slower and will surely require more time to reach the prefire vegetation condition. At these sites, it was possible to observe in the field that regeneration was only dominated by scrub species (Promis, 2019). Considering the climate change scenario (i.e., temperature rise and prolonged periods of drought) together with the fire impact, especially in those places where the severity was high, a change in forest composition may be expected, and the existence of *N. alessandrii* forests would be subordinate to the success of the sprouts generated by scrubland.

Three years after the fire, a tendency of recovery of the vegetation was observed, especially in those locations where the fire regime was nocturnal and the effect was low to medium. Although there was no record of the weather conditions during the development of the fire, which would have allowed correlating the degree of effect with the intensity of the fire, a direct relationship was observed between the time of occurrence of the fire and the damage produced. The highest severity of the fire occurred in those places where the fire developed during the day. On the other hand, in those places where it consumed the undergrowth and damaged parts of the trees, mainly in the stems without reaching the crowns (“El Desprecio”, “El Porvenir”, and “El Fin”), the fire occurred during the night. Based on what was observed in the field, only scrubland regenerated.

Taking an NDVI value of 0.5 as the lower limit to describe vigorous *N. alessandrii* forests (less than that value, there was only 3.1 ha, which represents 1.7% of the affected area), before the fire (January 2017), an area of 174.9 ha was covered by this type of forest. One year after the disturbance (January 2018), that area decreased to 49.7 ha; that is, there was a reduction close to 70%. Two years after the fire (January 2019), the surface area with NDVI values over 0.5 was 144.2 ha, showing a vegetation recovery process. After three years, *N. alessandrii* forests have recovered in terms, at least, of the greenness analyzed by the NDVI. This is consistent with that reported by Petropoulos et al. (2014), who observed that the spatial pattern NDVI after a fire in a Mediterranean environment generally shows a gradual but systematic return to the prefire conditions. In our study, this was confirmed when analyzing those sectors where the fire severity was low-medium (“El Desprecio”, “El Porvenir”, and “El Fin”). Before the fire, there was an area covered by *N. alessandrii* forests of 95.2 ha with an NDVI greater than 0.5; in 2018 (i.e., one season later), it was equal to 41.7 ha; in 2019 (i.e., two seasons later), it was 73 ha; and in 2020 (i.e., three seasons later), it was 74.2 ha. In contrast, when analyzing those sectors where the fire severity was high, before the fire, there was an area of *N. alessandrii* forests of 79.7 ha with an NDVI greater than 0.5; in 2018, it was equal to 8 ha; in 2019, it was 64.4 ha; and in 2020, it was 70.05 ha, showing a similar return to the prefire situation. This is an indication confirming that in those sectors where fire severity was low-medium, the postfire NDVI spatial pattern showed a systematic and more rapid return to predisturbance conditions when compared to those sectors where the fire severity was high. However, in those sectors where the effect was high, the return to prefire conditions accelerated. If it is considered that the forests of *N. alessandrii* are distributed naturally only on shaded slopes (Santelices et al., 2012), the relatively rapid recovery could be explained by this factor. Petropoulos et al. (2014) suggested that hillsides with shady exposures show a slightly faster recovery rate compared to sunny slopes. This could be due to more favorable microclimatic and hydrological conditions for vegetation growth in these areas in Mediterranean environments; on shady slopes, finer and deeper soils have been observed, and these conditions are more favorable for a greater growth of vegetation than on sunny slopes (Fox et al., 2008). However, it is necessary to evaluate the recovery of vegetation composition in the field. According to what was observed, the postfire vegetation was composed of sprouting *N. alessandrii* and other xerophytic species. In this context, it is suggested to carry out a study where the dynamics of regeneration after fire exposure are evaluated.

Conclusions

Of the three indices used to study severity after a fire in the forests of *N. alessandrii,* the most reliable index was the RdNBR, although the results were very similar to the dNBR and RBR. On the other hand, the spatial pattern of the postfire NDVI showed a relatively rapid vegetation recovery three years after the fire, especially in those sectors in which the severity of the fire was high, although it must be considered that this recovery may have been mainly related to the shrub layer. As a consequence of the fire, at least 15% of the *N. alessandrii* forests would have been lost. Postfire remote sensing analysis provides key information for restoring burned forests in which the intensity of the fire varied. In this way, the use of resources for restoration could be utilized more efficiently.

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Resumen

R. Santelices-Moya, A. Cabrera-Ariza, P. Silva-Flores, y R.M. Navarro-Cerrillo. 2022. Evaluación del efecto de un mega incendio forestal sobre los bosquetes remanentes de *Nothofagus alessandrii*, una especie en peligro de extinción de Chile Central, a partir de imágenes satelitales Sentinel-2. Int. J. Agric. Nat. Resour. 85-96. *Nothofagus alessandrii* es una especie en peligro de extinción que se distribuye naturalmente en un ambiente mediterráneo en Chile. En los últimos años, este territorio ha estado sujeto a los efectos del cambio climático, especialmente por un aumento de las temperaturas estivales y periodos prolongados de sequía. En el verano de 2017 se produjo un incendio de gran magnitud que consumió 184,000 ha y que afectó a una parte de los bosques de *N. alessandrii*. En este estudio se evaluó la severidad y la dinámica de recuperación de la vegetación posterior al incendio, mediante el uso de algunos índices espectrales con imágenes de Sentinel-2. El índice de combustión normalizado diferenciado (dNBR), el índice de combustión normalizado diferenciado relativo (RdNBR) y el índice de combustión relativizado (RBR) se calcularon antes y después del incendio. Además, el índice de vegetación de diferencia normalizada (NDVI) se calculó antes del incendio y tres años consecutivos después del incendio. La precisión de las clasificaciones de severidad del fuego se estimó usando la prueba kappa ($p<0,05$). Los tres índices de severidad mostraron una clasificación similar en la evaluación de la gravedad y la respuesta posterior al incendio. El área de quema baja-media en los bosques de *N. alessandrii* osciló entre 111,2 ha (RdNBR) y 130,3 ha (dNBR), y el efecto alto entre 46,1 ha (dNBR) y 66,0 ha (RdNBR), siendo equivalente en ambos casos, aproximadamente 11% del total. En cuanto al NDVI, la recuperación de la vegetación después de tres años del incendio muestra un retorno sistemático a las condiciones previas al incendio. La evaluación del efecto de un mega incendio forestal en los bosques restantes de *N. alessandrii* basada en Sentinel-2 ofrece la oportunidad de comprender mejor la gravedad del daño y el comportamiento de la vegetación después del incendio. Toda esta información ayudará a una mejor recuperación de estos bosques.

Palabras clave: Bosque mediterráneo, índices espectrales, restauración post-incendio, ruil, sensores remotos.

References

Arellano, S., Vega, J.A., Silva F.R.Y., Fernandez, C., Vega-Nieva, D., Alvarez-Gonzalez, J.G., & Ruiz-Gonzalez, A.D. (2017). Validation of the remote sensing indices dNBR and RdNBR to assess fire severity in the Oia-O Rosal (Pontevedra) wildfire in 2013. *Revista de Teledeteccion, 49*, 49–61. https://doi.org/10.4995/raet.2017.7137

Ariza, A., Salas Rey, J., & Merino de Miguel, S. (2019). Comparison of maximum likelihood estimators and regression models for burn severity mapping in Mediterranean forests using Landsat TM and ETM+ data. *Revista Cartográfica, 98*, 145–177. https://doi.org/10.35424/rcarto.i98.145

Arroyo, M.T.K., Riveros, M., Peñaloza, A., Cavieres, L., & Faggi, A.M. (1996). Phytogeographic relationships and regional richness patterns of the cool temperate rainforest flora of southern South America. In R. G. Lawford, et al. (Eds.), *High-Latitude rainforests and associated ecosystems of the west Coasts of the Americas: climate, hydrology, ecology and conservation*. (pp. 134–172). Springer, New York.

Barstow, M., Echeverría, C., Baldwin, H., & Rivers, M.C. (2017). *Nothofagus alessandrii*. The IUCN Red List of Threatened Species 2017: e.T32033A2808995.

Botella-Martinez, M.A., & Fernandez-Manso A. (2017). Study of post-fire severity in the Valencia region comparing the NBR, RdNBR and RBR indexes derived from Landsat 8 images. *Revista de Teledeteccion, 49*, 33–47. https://doi.org/10.4995/raet.2017.7095

Boucher J., Beaudoin A., Hébert C., Guindon L., & Bauce É. (2017). Assessing the potential of the differenced Normalized Burn Ratio (dNBR) for estimating burn severity in eastern Canadian boreal forests. *International Journal of Wildland Fire, 26*, 32–45.

Bustamante, R.O., & Castor, C. (1998). The decline of an endangered temperate ecosystem: the ruil (*Nothofagus alessandrii*) forest in central Chile. *Biodiversity and Conservation, 7*, 1607–1626.

CONAF. (2017). *Análisis del impacto de los incendios forestales ocurridos en enero y febrero de 2017 sobre los ecosistemas naturales presentes entre las regiones de Coquimbo y Los Ríos de Chile*. Informe Técnico, Santiago, Chile.

Congalton R.G., & Green K. (2009) *Assessing the accuracy of remotely sensed data. Principles and practices*. Second ed. CRC Press. Taylor & Francis, Boca Raton.

De la Barrera, F., Barraza, F., Favier, P., Ruiz, V., & Quense, J. (2018). Megafires in Chile 2017: Monitoring multiscale environmental impacts of burned ecosystems. *Science of The Total Environment, 637–638*, 1526–1536. https://doi.org/10.1016/j.scitotenv.2018.05.119

DMC. (2017*). Anuario Meteorológico 2016*. Dirección Meteorológica de Chile, Santiago, Chile.

Donoso, C., & Lara, A. (1996). Utilización de los bosques nativos en Chile: pasado, presente y futuro. In Armesto, J.J., Villagrán, C., & Arroyo M.K. (Eds.). *Ecología de los bosques nativos de Chile*. (pp. 363–388). Santiago, Chile: Editorial Universitaria.

Escuin, S., Navarro, R., & Fernández, P. (2008). Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images. *International Journal of Remote Sensing, 29*, 1053–1073. https://doi.org/10.1080/01431160701281072

Fox, D.M., Maselli, F., & Carrega P. (2008). Using SPOT images and field sampling to map burn severity and vegetation factors affecting post forest fire erosion risk. *CATENA, 75*, 326–335. https://doi.org/10.1016/j.catena.2008.08.001

Gao, L., Wang, X.F., Johnson, B.A., Tian, Q.J., Wang, Y., Verrelst, J., Mu, X.H., & Gu X.F. (2020). Remote sensing algorithms for estimation of fractional vegetation cover using pure vegetation index values: A review. *Isprs Journal of Photogrammetry and Remote Sensing, 159*, 364–377. https://doi.org/10.1016/j.isprsjprs.2019.11.018

García-Duro, J., Manso, A., Cruz, O., Basant,a M., Casal, M., & Reyes O. (2016). Regeneración post-fuego en relación con la severidad del incendio en un área atlántica de Galicia. Bases para la restauración. *Cuadernos de la Sociedad Española de Ciencias Forestales, 42*, 129–140.

Harris, R.M.B., Remenyi, T.A., Williamson, G.J., Bindoff, N.L., & Bowman, D.M.J.S. (2016). Climate–vegetation–fire interactions and feedbacks: trivial detail or major barrier to projecting the future of the Earth system? Wiley Interdisciplinary Reviews: *Climate Change, 7*, 910–931. https://doi.org/10.1002/wcc.428

Key, C., & Benson, N. (2006). Landscape Assessment (LA). General Technical Report RMRS-GTR-164-CD. In D. Lutes, et al. (Eds.), *FIREMON: Fire Effects Monitoring and Inventory System*. (pp. 1-55). USDA Forest Service, Rocky Mountains Research Station, Fort Collins, CO.

Leon, J.R.R., Van Leeuwen, W.J., & Casady, G.M. (2012). Using MODIS-NDVI for the modeling of post-wildfire vegetation response as a function of environmental conditions and pre-fire restoration treatments. *Remote sensing, 4*, 598–621.

Meng, R., Dennison, P.E., Huang, C., Moritz, M.A., & D'Antonio, C. (2015). Effects of fire severity and post-fire climate on short-term vegetation recovery of mixed-conifer and red fir forests in the Sierra Nevada Mountains of California. *Remote Sensing of Environment, 171*, 311–325. https://doi.org/10.1016/j.rse.2015.10.024

Miller, J.D., Knapp, E.E., Key, C.H., Skinner, C.N., Isbell, C.J., Creasy, R.M., & Sherlock, J.W. (2009). Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. *Remote Sensing of Environment, 113*, 645–656. https://doi.org/10.1016/j.rse.2008.11.009

Miller, J.D., & Thode, A.E. (2007). Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment, 109*, 66–80. https://doi.org/10.1016/j.rse.2006.12.006

Morgan, P., Keane, R.E., Dillon, G.K., Jain, T.B., Hudak, A.T., Karau, E.C., Sikkink, P.G., Holden, Z.A., & Strand, E.K. (2014). Challenges of assessing fire and burn severity using field measures, remote sensing and modelling. *International Journal of Wildland Fire, 23*, 1045–1060. https://doi.org/10.1071/WF13058

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., & Kent J. (2000.) Biodiversity hotspots for conservation priorities. *Nature, 403*, 853–858.

Parks, S.A., Dillon, G.K., & Miller, C. (2014). A New Metric for Quantifying Burn Severity: The Relativized Burn Ratio. *Remote Sensing, 6*, 1827–1844. https://doi.org/10.3390/rs6031827

Petropoulos, G.P., Griffiths, H.M., & Kalivas, D.P. (2014). Quantifying spatial and temporal vegetation recovery dynamics following a wildfire event in a Mediterranean landscape using EO data and GIS. *Applied Geography, 50*, 120–131. https://doi.org/10.1016/j.apgeog.2014.02.006

Promis, A., Olivares, S., Acuña, S., & Cruz, G. (2019). Respuesta temprana de la regeneración de plantas leñosas después del incendio forestal denominado "Las Máquinas" en la Región del Maule. *Gayana botánica, 76*, 257–262.

San Martín, J., Santelices, R., & Henríquez, R. (2013). *Nothofagus alessandrii* Espinosa, Ruil. Familia: *Nothofagaceae.* In Donoso, C. (Ed.) *Las Especies Arbóreas de los Bosques Templados de Chile y Argentina*. (pp. 391-401).Valdivia, Chile: Autoecología, Marisa Cuneo Ediciones.

Santelices, R., Drake, F., Mena, C., Ordenes, R., & Navarro-Cerrillo, R.M. (2012). Current and potential distribution areas for *Nothofagus alessandrii*, an endangered tree species from central Chile. *Ciencia e Investigación Agraria, 39*, 521–531.

Santelices, R., Espinoza, S., Cabrera, A., & Magni, C. (2018). Gestión de riesgo como herramienta para la conservación de los bosques de *Nothofagus alessandrii*, una especie en peligro de extinción de Chile central. *Interciencia, 43*, 144–150.

Torres, J., Gonçalves, J., Marcos, M., & Honrado, J. (2018). Indicator-based assessment of post-fire recovery dynamics using satellite NDVI time-series. *Ecological Indicators, 89*, 199–212. https://doi.org/10.1016/j.ecolind.2018.02.008

Úbeda, X., & Sarricolea, P. (2016). Wildfires in Chile: A review. *Global and Planetary Change, 146*, 152–161. https://doi.org/10.1016/j.gloplacha.2016.10.004

Valencia, D., Saavedra, J., Brull, J., & Santelices, R. (2018). Severidad del daño causado por los incendios forestales en los bosques remanentes de *Nothofagus alessandrii* Espinosa en la región del Maule de Chile. *Gayana Botanica, 75*, 531–534.

Veraverbeke, S., Lhermitte, S., Verstraeten, W.W., & Goossens, R. (2010). The temporal dimension of differenced Normalized Burn Ratio (dNBR) fire/burn severity studies: The case of the large 2007 Peloponnese wildfires in Greece. *Remote Sensing of Environment, 114*, 2548–2563. https://doi.org/10.1016/j.rse.2010.05.029