Evaluating the Effects of Forest Cover Changes on Sediment Connectivity in a Catchment Affected by Multiple Wildfires

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Abstract Wildfire-related impacts on the hydrogeomorphic properties of river basins is scarcely studied in South American sites. Fire affects river systems by altering the forest cover, decreasing the soil infiltration capacity, modifying the sediment yields and leading to channel instability. To study the effect of the disturbance in the sediment routing, the analysis of changes in sediment connectivity, i.e. the degree of linkage between source and sink areas, has been recently used. The main aim of the present research is to adapt and apply the Index of Connectivity (IC) in a Chilean catchment affected by subsequent wildfires in 2002 and 2015. Specific objectives involve the derivation of fire severity maps of both wildfires, and the development of a weighting factor, which properly represents the impedance to sediment fluxes. We made use of satellite images and sampling plots to carry out the fire severity maps and then the Normalized Difference Vegetation Index (NDVI) for the computation of the weighting factor maps used in the connectivity analysis. The results demonstrated not only the applicability of this approach, which permitted to highlights the changes in IC patterns but even the predominant changes in forest cover as well as the preferential sources of sediment within the basin.

Keywords Wildfires · Fire severity · Land cover change · Sediment connectivity · Chile

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1 Introduction

Among large natural disturbances affecting river systems, wildfires are often indicated as major agents for land and soil degradation (Shakesby 2011) and for geomorphological changes in densely vegetated catchments (Neary et al., 2005). The hydrogeomorphic response to wildfires has been deeply studied in forested catchments: decrease of root resistance; reduction of soil infiltration capacity (Swanson, 1981), exacerbation of soil erosion (Shakesby, 2011), water runoff and sediment yield increase (Benavides-Solorio and MacDonald, 2001; Neary et al., 2005) are few out of many effects reported in areas affected by wildfire. Furthermore, specific effects on river morphology have been documented due to the increase of in-channel wood recruitment (Benda et al., 2003) and the alteration of channel stability (e.g. channel aggradation) (DeBano et al., 1998).The effects of fire strongly depend on the intensity, duration, pre-fire disturbance history (Brogan et al., 2019) as well as from the topography, vegetation, geology and climate of the area affected (Swanson 1981). In addition, human activities are becoming a further propellant factor for wildfire's occurrence and damages. In this context, the assessment of fire severity, which often encompasses the properties of intensity and duration, is extremely important to quantify the fire-related impact and still represents a major challenge.

In river basins, the spatial distribution of wildfire-induced effects, especially those regarding sediment transfer, is determined by the spatial arrangement of the sediment sources and their capability to deliver sediment into the stream network. In the cascade process, the chance of sediments to reach specific compartments of the catchment is strictly related to the structural properties of the system itself (Hooke 2003; Heckmann et al., 2018). The evolving studies in the field of connectivity are becoming fundamental to understand the efficiency of sediment transfer within geomorphic systems (Heckmann et al., 2018). The assessment of the degree of linkage between two compartments, potentially (de)coupled, can be ensured thanks to the Index of Connectivity (IC) (Borselli et al., 2008; Cavalli et al., 2013). The IC performs a characterization of the sediment paths prone to deliver sediment from sources to sinks primarily according to the topographic conditions. Initially, such topography-based index gave positive results in alpine catchments, typically with steep slopes, high sediment availability and scattered vegetation (Cavalli et al., 2013; Rainato et al., 2018). Afterwards, the IC have been widely used to analyse various catchments after natural or human disturbances (Heckmann et al., 2018; Persichillo et al., 2018; Llena et al., 2019). Nevertheless, the analysis of sediment connectivity in response to wildfires is scarcely considered (Ortíz-Rodríguez et al., 2019) even if their capability to mobilize sediments have been largely documented.

The present study aims to analyse the variations in sediment connectivity in a catchment affected by two subsequent wildfires. Specific objectives regards (i) the assessment of fires severity (ii) the development of IC by means of open source Digital Elevation Model (DEM) and satellite images (iii) comparison of wildfire and IC spatial patterns for land management purposes.

2 Study Area

The study area is the Rio Toro catchment, an 18 km^2 basin located in southern Chile (Araucanía Region). The Chilean territory is known for the high occurrence of large wildfires (between one and eight thousands per year, in the last 20 years), which represents a cause of loss of native forests, a major threat for human settlements and a destabilizing factor for river systems (Úbeda and Sarricolea 2016; Mazzorana et al. 2019). In this context, the Rio Toro catchment was affected by the occurrence of two major wildfires in 2002 and 2015. The former burned almost 20000 ha in the Araucanía Region (González et al., 2005). The climate of the area is temperate warm humid with mean annual precipitation of 2480 mm (Comiti et al., 2008; Mao et al., 2008), promoting the growth of endemic *Nothofagus* spp. in the downstream part and *Araucaria araucana* in the uppermost part. The thick understorey is mainly composed by native bamboo (*Chusquea* spp.), which takes advantage of the large gaps offered by *Araucaria aruacana* forest (Ulloa et al., 2015). The catchment's altitude ranges from 762 m a.s.l. in the northern areas to 1816 m a.s.l. The water course flows from S–E to N–W for about 7 km, exhibiting plane-bed/step-pool channel morphology (Comiti et al., 2008).

3 Materials and Methods

The study was carried out in two main phases: i) the assessment of fire severity for both wildfires (2002 and 2015) by means of the spectral vegetation index difference Normalized Burn Ratio (dNBR)(Key and Benson, 2006) and ii) the analysis of sediment connectivity changes thanks to the IC (Fig. 1).

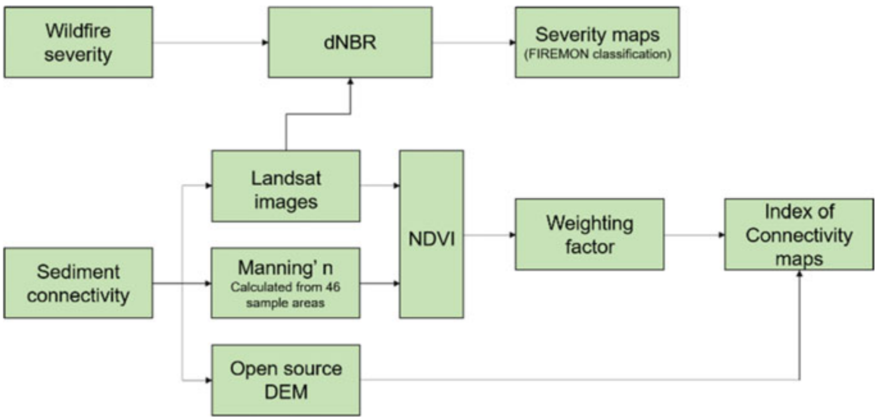

Fig. 1 Flowchart describing the procedure to carry out the wildfire severity and the IC

The two phases rely upon open-source remote sensing data and field surveys in order to carry out the fire severity and IC maps.

3.1 Fire Severity

The severity of the two wildfires has been assessed using the classification system FIREMON (Fire Effects Monitoring and Inventory System) included in the Landscape Assessment section (Key and Benson, 2006). This approach requires aggregate information about fire effects among large areas by using remote sensing data to perform the dNBR. The dNBR, calculated using Landsat 7 products, allows the quantitative detection of the differences of reflectance between the pre and post-fire surfaces (further information in Key and Benson, 2006). The resulting fire severity maps have been presented by highlighting only the high—moderate high classes due to major interest.

3.2 Index of Connectivity

The analysis of sediment connectivity has been carried out thanks to the IC (Borselli et al., 2008; Cavalli et al., 2013) in order to adapt it to mountainous catchments, typically showing lack of vegetation, steep slopes and high sediment availability. The IC is computed according to the logarithmic form described in the Eq. (1):

$$IC = \log_{10} \frac{\left(\bar{W}\bar{S}\sqrt{A}\right)}{\left(\sum_i \frac{d_i}{S_i W_i}\right)} \tag{1}$$

where W is the weighting factor, representing the impedance to sediment fluxes given by the structural characteristics of surface roughness, S (m/m) is the slope, A (m^2) is the area contributing to a specific point, d_i (m) is the length of the path between the upslope and downslope component (represented by numerator and denominator, respectively).

The topographic information required to derive the IC is given by an open source DEM obtained from the satellite mission ALOS PALSAR. The DEM has 12,5 m resolution and it can be downloaded from the Alaskan Facility Service (ASF) website (https://www.asf.alaska.edu). The DEM constitutes the basis for the IC analysis which accounts the land cover changes for two periods before and after both wildfires to carry out coherent Weighting factors (see Sect. 3.2.1). The IC changes have been verified with the Wilcoxon signed ranked in order to test statistical differences in the medians between pre and post-wildfires years (p-value < 0,05). The differences have been classified in seven main classes to highlight the major differences in IC.

3.2.1 Weighting Factor

The weighting factor (W factor) represents the impedance to sediment fluxes, which can be derived from the measure of the surface roughness. In this work, the W factors have been carried out according to a methodology involving first the computation of a Manning's coefficient for the overland flow for 46 ground samplings and then the propagation of the coefficient to the whole catchment thanks to the correlation with the Normalized Difference Vegetation Index (NDVI). Similar methodologies have been proposed by other authors (e.g. Mishra et al., 2019) to extend land cover parameters (such the C factor in the Revised Universal Soil Loss Equation) at catchment scale by correlating them with the NDVI. In this study, the Manning's n for the overland flow was used instead of the much-used C factor to represents the impedance to sediment fluxes. The Manning's n was calculated using the pre-existing adjustment tables of Arcement and Schneider (1989), which calculate an overall coefficient (n) according to specific parameters observed in the field. The coefficient was calculated for 46 sampling plots (10 × 10 m) scattered all over the Rio Toro catchment. Finally, four W factor maps have been produced to support the computation of IC in four different years (pre and post-wildfires, 2001, 2003, 2015, 2016).

4 Results and Discussion

Our results regarding the severity of the two wildfires show that in both cases the areas classified as high-moderate high covers more than 20% of the whole catchment. However, as expected, an outstanding difference is evident between the results of the two wildfires (Fig. 2). The wildfire's high-moderate high severity areas, in fact, are much more widen in 2002 (Fig. 2a) than 2015 (Fig. 2b), 12 km^2 and 3,6 km^2, respectively. This outstanding difference could be caused by the intrinsic bias in the 2015 severity map, which inevitably takes into account the 2002 post-wildfire condition for the computation of the dNBR. This is in accordance with Brogan et al. (2019), who defined as the pre-disturbance history can drastically impose either a decrease or an increase of catchment's sensitivity. The difference of IC (DoIC) values are also presented in Fig. 2. The DoIC highlights similar spatial patterns among the IC variations and the high-moderate high fire severity areas. The areas classified as high and medium-high fire severity partially corresponds to the areas where the IC difference is higher as well, which are mainly located in the central part of the catchment. In both maps, there is an evident increase in IC values: mean values from −2,32 (2001) to −2,16 (2003) and from −2,24 (2015) to −2,18 (2016); maximum values from 2,52 (2001) to 2,59 (2003) and from 2,55 (2015) to 2,57 (2016). This results is mainly associated with the important reduction of forest cover and major increase of potential erodible areas. The difference in IC was documented also in the Mexican site studied by Ortíz-Rodríguez et al. (2019), which also found similar proportion between the higher IC patterns and the burned areas. The higher differences in IC are more evident along the slopes close to the channels, which represent the primary

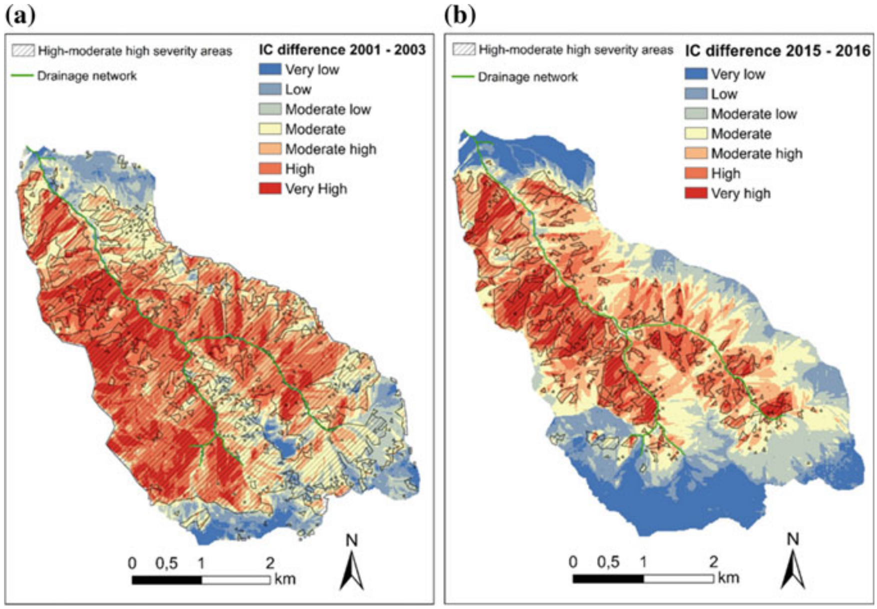

Fig. 2 Difference of the Index of Connectivity calculated between pre and post-wildfire periods: **a** first wildfire in 2002; **b** second wildfire in 2015. High—moderate high fire severity areas are represented by dashed areas

sink for the sediment fluxes from hillslope-channel perspective. Considering these results, the Rio Toro catchment could face two intertwined trends that will promote the sediment yields towards the stream network: the increase of sediment connectivity suggested by higher IC values and the increase of slope erodibility due to the loss of forest cover.

5 Conclusions

In the present study, an application of the Index of Connectivity have been carried out in order to assess the importance of land cover changes, caused by a natural disturbance, to the sediment connectivity. The strong relationship between the two components was evident from the results, which highlights the spatial overlaps between IC changes and fire severity. Indeed, when considering the analysis of sediment dynamics in forested catchments, the vegetation characteristics cannot be neglected. Particularly, this correlation is even more important in post-disturbance scenarios, where the variations of land cover and sediment connectivity are emphasised. In this way, further analysis in the field of sediment connectivity applied in wildfire-affected areas could provide helpful information for land managers.

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