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SHORT NOTE: FIRE EFFECTS ON ROCK WEATHERING IN THE NORTH PATAGONIAN ANDEAN RANGE

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ABSTRACT

Fire-induced rock exfoliation is a rapid mechanical weathering process characterized by an uneven heating and thermal expansion stress that causes the detachment of rock peels, flakes or spalls. We examined 18 granitoid erratic blocks on a gradient of fire severity in a burned inselberg near El Bolsón, during March 2023. Among them, 13 blocks showed fire spalling, producing 0.1 to 6 kg/m^2 of sediment on rock surfaces with an average of 1.72 kg/m^2. The incidence of fire spalling showed a more pronounced occurrence within areas of higher severity above dNBR 800. This study is the first mention of fire-induced weathering in the Patagonian Andes, which underlines the need to investigate the intricate relationship between forest fires and the denudation of vegetated outcrops in the region.

INTRODUCTION

Soil erosion following fires is a widely recognized phenomenon in the physical environment (Shakesby and Doerr, 2006; Fernandez and Vega, 2011; among others). In contrast, the rock weathering effects resulting from the intense heat of forest biomass fires have received less attention with sporadic mentions in the global literature (Blackwelder, 1927; Ollier and Ash, 1983; Buckman *et al.*, 2021; Shtober-Zisu and Wittenberg, 2021; Mol and Grenfell 2022; among others). This unique instance of rapid and catastrophic thermoclastic rock flaking process (Anderson, 2019) remains largely unexplored worldwide including both the Patagonian and Latin American contexts.

During forest fires, temperatures can surge to 850°C at the soil-litter interface (Debano, 1981), or even reach 1100°C within the forest canopy (Countryman, 1964). Quartz expands more significantly than feldspar and hornblende, with a 3.76 percent volume increase from room temperature to 570°C (Winkler, 2013). Consequently, quartz-rich rocks, under a fire, possess greater expansion potential and a heightened propensity to spall. Fire energetically dislodges cm-scale rock slabs, impacting a substantial proportion of exposed surfaces during a fire event (Shakesby and Doerr, 2006; Kendrick *et al.*, 2016). Recent research (Van der Beek *et al.*, 2001; Buckman *et al.*, 2021) has illustrated that fire-induced rock spalling yields 10-100 times

more sediment than any other non-fire related weathering process.

Every summer fires devastate large vegetated areas of the North Patagonian Andean Range (Kitzberger and Veblen, 2003; Kitzberger *et al.*, 2005; Mermoz *et al.*, 2005; Veblen *et al.*, 2008). In March 2023, a fire broke out in the Loma del Medio - Rio Azul Forest Reserve (LMRAFR), affecting various forest ecosystems in the vicinity of the city of El Bolsón, province of Rio Negro. Our initial observations on outcrops in the aftermath (Fig. 1) underscores the significance of fire-induced rock spalling as a pivotal sediment production mechanism within the affected area. Consequently, the aim of this short contribution is to provide an inaugural acknowledgment of the fire-induced rock spalling process in the Patagonian region and to estimate the amount of new sediment yield in relation to the severity of this fire event.

Figure 1. Granitoid erratic blocks surveyed after the LMRAFR fire (refer to fig. 2 for location details), with information provided for each block, including the estimated surface area and the total weight of sediment spalled by fire.

STUDY AREA

During 2021 and 2023 summers, notable forest fires in the rural-urban interface significantly impacted the vicinity of El Bolsón city, located in the Río Negro province of Argentina, adjacent to the Andean range (Lopez and Madariaga 2021; MAyDS 2021; Mohr Bell 2021). The most recent fire event, commencing accidentally in March 2023 on a camping site, exerted its influence on the LMRAFR, an inselberg orientated N-S between the Azul and Quemquemtreu rivers (Fig. 2). This low altitude but relatively high relieved inselberg (350-650 m a.s.l), shows steep slopes composed by tertiary red sandstones and other continental strata outcrops from the Rio Foyel Formation, a lower unit of the Nirihuau sedimentary basin (Asensio *et al.*, 2010). This inselberg was shaped by glacial abrasion processes, alongside sandur terraces deposits (Muñiz Fredes, 2020) adorned with granitic erratic blocks all partially concealed by forest. The vegetation is mainly dominated by pure and mixed *Austrocedrus chilensis* and *Nothofagus dombeyi* forests.

METHODOLOGY

To distinguish the fire-induced rock spalling process from other fire-related processes, we chose to survey granitoid erratic blocks scattered above the glacial terrace deposits, sandur terraces. During July 2023, we used an existing 2 km trail running along the northern part of the LMRAFR burned area to optimize sampling while covering a varying range of fire severity sectors. We sampled 18 granitoid erratic blocks and for each of them we collected the spalled clasts larger than 10 mm in a bag and weighed them with a spring scale. Sediments finer than 10 mm were negligible, and given its granulometry and condition (mixed with top soil) it was not possible to guarantee the recollection of the total fraction. Subsequently, we measured the block's dimensions — length (L), height (H), and depth (D) — with a measuring tape to estimate its surface area using the following basic prismatic formula: *Block surface (m2)=2(H×L)+2(H×D)+(D×L)*.

Fire severity depends on the interactions between burning, especially its duration and intensity, and the characteristics of the biomass, soil, terrain and local climate (Shakesby and Doerr, 2006). It was estimated through Sentinel 2A satellite imagery analysis. For this, two images acquired before and after the fire were selected to be as close as possible to the time of the fire, thereby minimizing phenological differences in vegetation (Chuvieco, 2016). On Google Earth Engine platform the images underwent orthorectification and atmosphere, cloud and snow correction. Then, the Normalized Burn Ratio (NBR) was utilized for fire severity estimation as: *NBR = (NIR - SIR)÷ (NIR + SWI)* (Key and Benson, 2006), where NIR represents the reflectance in near-infrared (Sentinel, band 8) and SWIR the short-wave infrared (Sentinel, band 12). The difference index value was calculated as: *dNBR = NBR (pre-fire) - NBR (post-fire)*.

RESULTS

The sampled erratic blocks along the trail (Table 1) displayed varying sizes ranging from 0.1 to 6 m^3 and a mean value of 0.91 m^3 (StD=1.46 m^3). A significant majority (73%) exhibited rock fire-spalling. On average, the fire-spalled boulders yielded clastic fragments weighing 5.35 kg per block (StD=4.9 kg). Considering the surface of the block, the total average yield value of new sediment in all the boulders affected by rock fire-spalling was 1.72 kg/m^2 (StD=1.83 kg/m^2).

The most notable rock detachment recorded resulted in a flake of 47 mm thickness, while this thickest flake of each erratic block affected by rock fire-spalling resulted in an average value of 26 mm (StD=13 mm). Moreover, a distinct pattern emerged between fire severity and the fire-spalling observed on the surveyed erratic blocks (Fig. 3). Notably, a significant increase in the quantity of rock peeling material became evident beyond a dNBR value of 800.

DISCUSSION

Fire can be an important rock weathering agent but much of what is known was based on descriptions rather than quantitative data (Shakesby and Doerr, 2006). Recent attempts were made to fill this gap (Buckman *et al.*, 2021; Shtober-Zisu and Wittenberg, 2021; Mol and Grenfell, 2022). We contribute in this sense by reporting an average of 1.72 kg/m^2 of fire-induced spalled rock produced in erratic granitoid blocks in the March 2023 fire event in northern Patagonia, Argentina. Furthermore, this process tended to increase with fire severity greater than 800 dNBR index.

The fire-induced rock spalling process on granitoid erratic blocks constitutes just one facet of the fire's impact on the LMRAFR outcrops. Among this granitoid boulder the tertiary sandstone formations present in the LMRAFR burned area showcase a multitude of distinct weathering and erosion phenomena. Within these outcrops, prior root bioturbation, the turnover of deceased burnt trees, fire-spalling, and mass wasting synergize due to their softer lithification and steep eastward dip.

Reflecting on the rock peeling observed on granitic erratic blocks and the intensified sandstone outcrop erosion prompted by the fire, our findings align with those of Buckman *et al.* (2021) and Van der Beek *et al.* (2001).

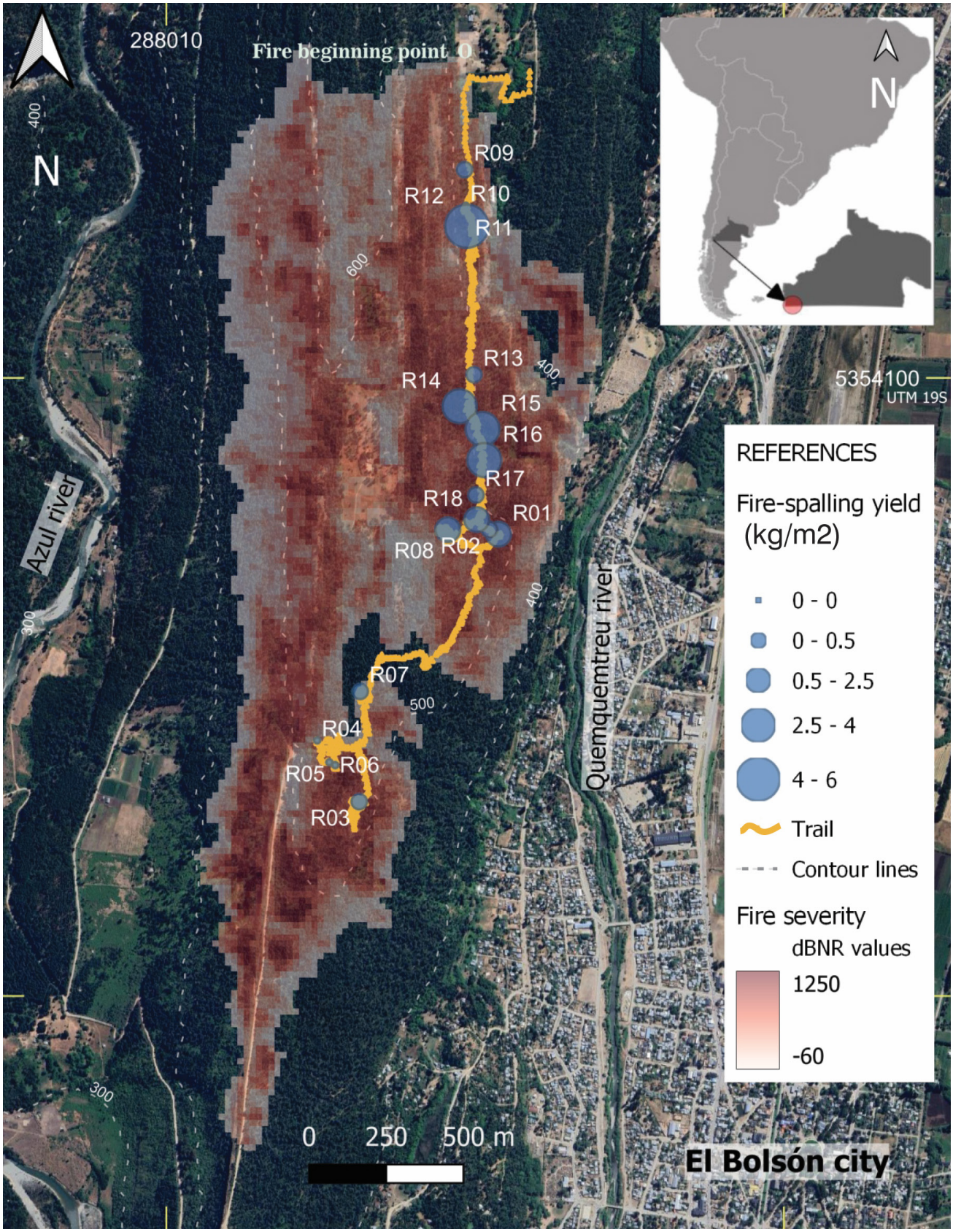

Figure 2. Study area, fire-induced rock spalling production by sampling points and fire severity analysis.

They propose that fire, as a disturbance, serves as a significant driving force behind physical weathering. This catastrophic thermoclastic phenomenon has been underestimated not only in arid regions (Buckman *et al.*, 2021) but also in densely vegetated temperate environments (Van der Beek *et al.*, 2001).

# Erratic block	Location	dNBR	Block Volume(m^3)	Block surface (m^2)	Max. spall thick (mm)	Total spalled (kg)	Spalled by block surface (kg/m^2)
R01	-41,94144303;-71,54430399	661.6	1.23	5.54	30	6.5	1.17
R02	-41,94129903;-71,54465603	881.7	5.24	15.74	10	2	0.13
R03	-41,94911197;-71,55005498	752.3	0.12	1.18	10	0.5	0.42
R04	-41,94729201;-71,551626	308.5	0.13	1.25	0	0	0
R05	-41,947939;-71,55117698	715.6	0.13	1.25	0	0	0
R06	-41,94802802;-71,55095201	714.9	0.13	1.25	0	0	0
R07	-41,94590103;-71,54988902	785.4	0.08	0.92	20	0.2	0.22
R08	-41,94126701;-71,54628203	855.4	0.55	3.44	50	8	2.33
R09	-41,93079902;-71,54520999	800.4	0.32	2.24	17	0.4	0.18
R10	-41,93184801;-71,54520697	644.9	0.05	0.63	0	0	0
R11	-41,93215697;-71,54502802	703.3	0.7	3.88	0	0	0
R12	-41,93244497;-71,54519096	659.5	0.1	1.04	20	6.2	5.96
R13	-41,93677397;-71,54507898	712.9	1.6	6.8	20	1.2	0.18
R14	-41,93768098;-71,54567803	902.8	0.53	3.16	29	9.5	3.01
R15	-41,93836402;-71,544809	860.7	0.86	4.32	47	17	3.94
R16	-41,93927002;-71,54477899	955.3	0.6	3.4	35	10.5	3.09
R17	-41,94028096;-71,54514201	872.8	3.07	10.88	34	4.5	0.41
R18	-41,94099803;-71,54514402	998	0.31	2.21	20	3	1.36
	Average	765.9	0.91	3.84	26.31	5.35	1.72
	Std Average	155.3	1.46	3.93	12.66	4.98	1.83

Table 1. Rock fire-spalling yield and area of 18 granitoid erratic blocks sampled at LMRAFR. Note: The reported average and StD only include erratic blocks with positive non-zero values.

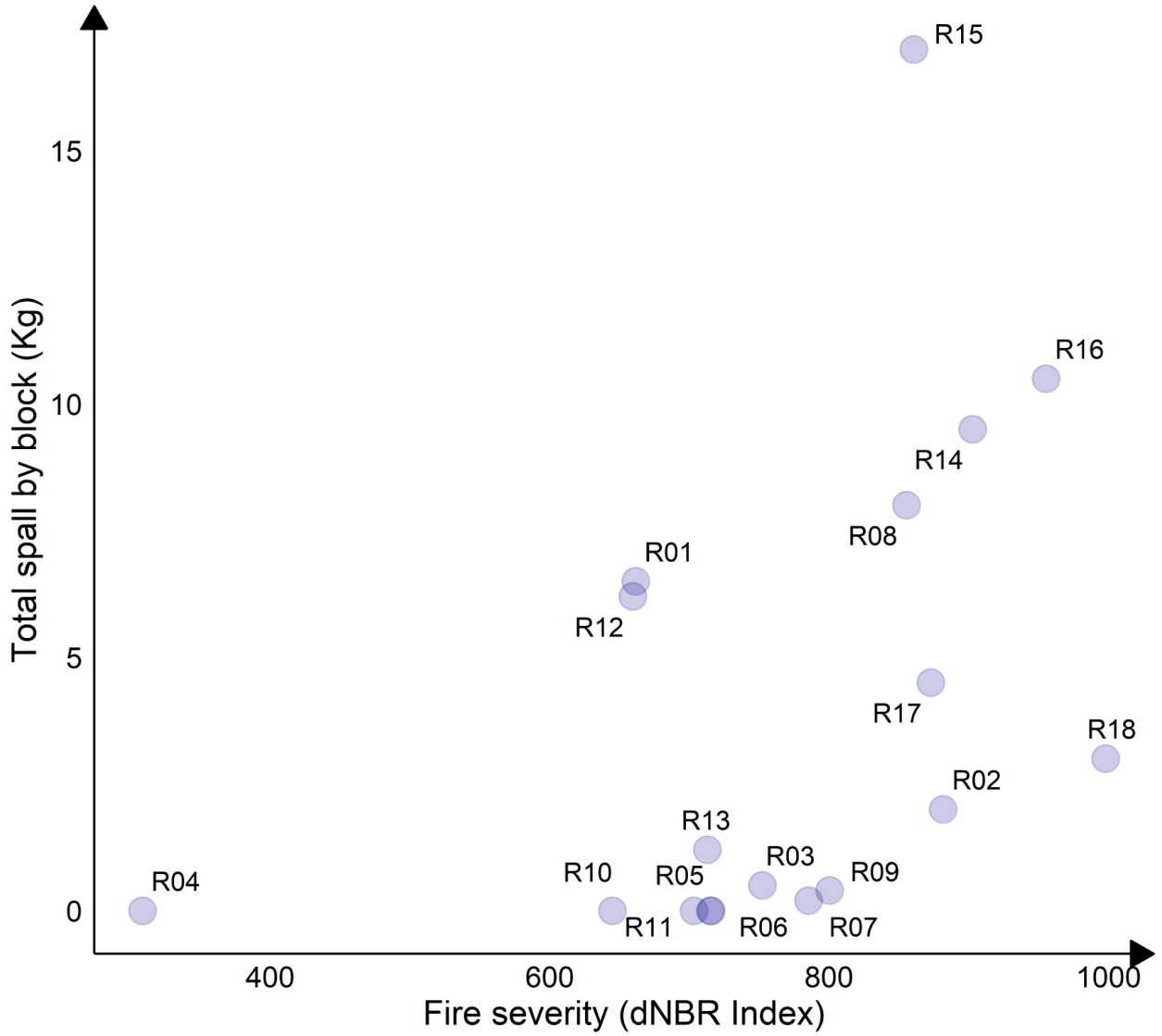

Figure 3. Sediment detachment by fire weighed on 18 granitic erratic blocks and its relationship with fire severity at the LMRAFR ($R^2 = 0.44$) March 2023 fire.

CONCLUSIONS

This contribution represents the first report of the effects of fire on rapid mechanical weathering processes in the North Patagonian Andes. On average, each granitoid erratic block studied at LMRAFR produced 5.35 kg of new fire-spalled sediments. Further studies should be directed to revisit the granitoid batholith outcrops that are widespread in the studied region in order to describe and quantify rock fire-spalling traces related to recent or ancient fires.

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