Science of the Total Environment 547 (2016) 345–355

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impacts of land-use and land-cover changes on rockfall propagation: Insights from the Grenoble conurbation

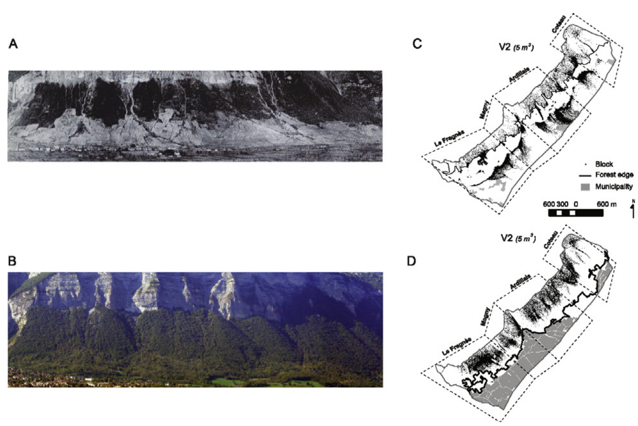
Jérôme Lopez-Saez [a,*], Christophe Corona [b], Nicolas Eckert [c], Markus Stoffel [d,e,f], Franck Bourrier [a], Frédéric Berger [a]

[a] Université Grenoble Alpes, Irstea, UR EMGR, 2 rue de la Papeterie, — BP76, F-38402 St-Martin-d'Hères, France
[b] Centre National de la Recherche Scientifique (CNRS), — UMR 6042, — GEOLAB, 63057 Clermont-Ferrand cedex, France
[c] Université Grenoble Alpes, Irstea, UR ETNA, 2 rue de la Papeterie, — BP76, F-38402 St-Martin-d'Hères, France
[d] University of Geneva, — Institute for Environmental Sciences, Climatic Change and Climate Impacts, 66 Boulevard Carl-Vogt –CH, 1205 Geneva, Switzerland
[e] University of Geneva, — Department of Earth Sciences, 13 rue des Maraîchers, CH, 1205 Geneva, Switzerland
[f] University of Bern, — Institute of Geological Sciences, — CH-3012 Berne, Switzerland

HIGHLIGHTS

- Impacts of LULC changes on rockfall propagation have received little interest.
- Reveal that the disappearance of viticultural landscapes and intense afforestation
- Resulted in a significant increase of rockfall return period
- Forests can indeed have significant protection function.
- Inclusion of LULC changes in hazard assessments in the future

GRAPHICAL ABSTRACT



Disappearance of viticultural landscapes and intense afforestation between 1850 (A) and 2013 (C) modified the spatial distribution of e.g. 5 m^3 rockfalls (B, D) for the slope of Crolles (French Alps) and significantly reduced rockfall hazard despite the continuous expansion of the urban front.

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form 29 December 2015
Accepted 29 December 2015
Available online xxxx

Editor: D. Barcelo

Keywords:
Peri-alpine conurbation
Land use and land cover changes
Rockfall modeling

ABSTRACT

Several studies have debated the incidence of global warming on the probability of rock instability, whereas the impacts of land use and land cover (LULC) changes on rockfall propagation and associated hazards have received comparably little interest. In this study we evaluate the impacts of LULC changes on rockfall hazards on the slopes above the village of Crolles (Chartreuse massif, Grenoble conurbation, French Alps) through a three-level approach: (i) diachronic landscape analysis for four different periods of the past (i.e. 1850, 1956, 1975, and 2013), (ii) computation of 3D rockfall simulations taking explicitly account of reconstructed LULC changes, and (iii) resulting changes in rockfall hazards over time. We reveal that the disappearance of viticultural landscapes (relating to the decline of cropping areas during the interwar period) and intense afforestation of the steepest upper portion of the slope resulted in a significant increase of rockfall return period associated to a gradual decrease of mean kinetic energy at the level of the urban front of Crolles. According to the Eurobloc methodology, the degree of hazard decreased significantly despite the continuous and rapid urban sprawl on the slopes. These

* Corresponding author.

http://dx.doi.org/10.1016/j.scitotenv.2015.12.148

Rockfall propagations
Protection forest

results underline that forests can indeed have significant protection function but also call for a more systematic inclusion of LULC changes in hazard assessments in the future.

1. Introduction

Rockfall is commonly defined as the detachment of a rock fragment from a steep rockwall (Selby, 1993) which then travels down the slope to a variable distance by bouncing, falling or rolling (Varnes, 1978). In general, fragmental rockfall involves relatively small detachments of isolated rocks or/and boulders with maximum volumes normally remaining <30 m^3 (Berger and Dorren, 2007). Rockfall is difficult to predict due to its sudden occurrence, lack of reliable precursor signals, poor information on the internal structure of the rock mass, and the multitude of triggering factors such as freeze–thaw cycles of water, melting of snow or permafrost, temperature changes, intense rainfall, stress relief following deglaciation, root penetration, and wedging (Matsuoka and Sakai, 1999; Lambert and Nicot, 2011). Additionally, owing to its high propagation speed and related risks for infrastructure (Harris et al., 2001) and populations, it constitutes one of the most hazardous geomorphic processes in mountainous environments. As for other mass movements, evaluating rockfall hazard includes a determination of occurrence location, actual size of the event, probability of occurrence, runout distance, and energy of time, and all this for a given period of time. The evaluation of rockfall risks then also includes the potential impact on exposed elements such as people, buildings, or transportation corridors (Dussauge-Peisser et al., 2002).

In the context of rapid environmental changes, several studies have debated the incidence of global warming on the probability of rock instability and the impacts of climate change on the triggering of rockfalls and rock avalanches (Huggel, 2009; Allen and Huggel, 2013; Stoffel et al., 2014). These analyses were mostly based on the retrospective analysis of historical chronicles and supported by the exceptionally warm summer of 2003 when largely increased rockfall activity has been reported throughout the Alps, especially at high elevations and on north-facing slopes (Gruner, 2004; Ravanel and Deline, 2010). Numerous case studies reporting spectacular rock and ice falls in the Alps further support this view (see Stoffel et al., 2014 for a detailed review). Thus, Deline et al. (2012) attributed 55% of the rockfalls observed in the Mont-Blanc massif in 2007 and 2008 to permafrost degradation, and Allen et al. (2009) found that 13 out of 19 rockfalls investigated in New Zealand originated from marginal permafrost areas. On the other hand, based on rockfall inventory data from Switzerland and Austria, Gruner (2004) and Sass and Oberlechner (2012) stated that a generally increasing frequency of rockfalls at present is neither recognizable nor to be expected in the near future.

Paradoxically, the impacts of land use and land cover (LULC) changes on rockfall propagation and associated hazards has remained only poorly discussed so far. Yet, LULC changes are considered as one of the most rapid drivers of global change (Slaymaker, 2011), especially in mountainous environments of Western Europe where slopes experienced a decrease in total acreage of cultivated areas (MacDonald et al., 2000), an increase in forested areas (Didier, 2001) and, in the industrialized and populated valleys, rapid urban densification (e.g. Falcucci et al., 2007; Bucała, 2014). Hillside instability, with potential consequences on rock fall propagation, tends to be amplified in areas of environmental land use conflicts due to enhanced erosion (Pacheco et al., 2014). In the case of landslides, by contrast, changes in LULC have indeed been identified as having an effect as predisposing factors on landslide occurrence (Glade, 2003; Beguería, 2006), but that they may also control the spatial distribution of consequences. Furthermore, land cover type has been recognized to significantly affect rockfall runout distance as a result of changes in restitution coefficients (Dorren, 2012a, 2012b; Perret et al., 2004) and thus areas at risk.

In this study, the impacts of LULC changes on rockfall propagation were investigated with a retrospective analysis. In a first step, LULC changes have been quantified for the slopes of the Chartreuse Massif (French Alps) for four different periods since 1850. This area has undergone (i) an intense agro-pastoral decline since the mid-19th century and (ii) a rapid periurbanisation – related to the vicinity of the Grenoble conurbation (500,000 inhabitants) – since the 1950s. Using the documented changes in LULC as input parameters, we then simulated rockfall trajectories for four different dates (1850, 1956, 1975, 2013) with the probabilistic process-based rockfall trajectory model RockyFor3D. This analysis then allowed determination of return periods and mean kinetic energy of rockfalls and therefore also definition of associated risk at the urban front of Crolles for each of the time steps and different block sizes (from 1.2 to 17 m^3).

2. Study site

The village of Crolles (45°17′09″N, 5°53′01″E) is located in the Grenoble conurbation on the southeastern slopes of the Chartreuse Massif (French Alps; Fig. 1A). The municipality extends from the «Bec Margain» (1036 m a.s.l.) to the Isère River (220 m a.s.l.) and covers an area of 14.2 km^2, three of which are located on the slopes of the Chartreuse massif (Fig. 1B). Since the 1950s, LULC on these concave talus slopes (250–600 m a.s.l.) have changed substantially in a way which can be considered typical for south-facing slopes in the French Prealps.

Covered with vineyard (Fig. 1C) since the mid-19th century, these slopes have experienced a rapid agropastoral decline during the interwar period, followed by intense periurban expansion since the mid-20th century. At Le Fragnès, Magny, Ardillais, and Le Coteau, neighborhoods started to spread upslope (Fig. 1D), thereby inducing a sharp increase (+864%) of local population (964 inhabitants or 67 persons km^{-2}, in 1946 against 8344 inhabitants or 588 persons km^{-2} in 2011).

The village of Crolles has constantly faced rockfall hazards as reflected in toponymy, since the root of Crolles, *corrotulare*, literally means *to roll a block* in Latin language. Rockfalls are released from a 300 m-high sub-vertical cliff made of thick-bedded limestones and marls from the upper Jurassic period (Dussauge-Peisser et al., 2002). Strata dip gently inward and three sub-vertical discontinuity sets can be observed at the site, one parallel to the direction of the cliff surface, and two others crossing it. The most common rockfall mechanisms are wedge failures, initiated on these two crossing sets, tower toppling and overhang failures, where the succession of limestone and marls suffers from differential erosion (Dussauge-Peisser et al., 2002). Archival records report number of rockfall events since 1900 with rockfall fragments varying from clasts with edge lengths of only a few decimeters to blocks with volumes >30 m^3. Fresh blocks, recent impact craters on the ground and visible growth disturbances (i.e. scars, decapitated trees) on the forest stand confirm ongoing intense rockfall activity during the last decades. As a consequence, three protective walls (with lengths of 400, 500, and 800 m, respectively) have been constructed since 1995 to reduce rockfall risk in the neighborhoods of Magny, Ardillais and Le Coteau, the latter one being reached by two blocks (>20 m^3) on 15 January 2012. Additionally a 1-km long protection wall is already planned for the next decade to protect Le Fragnès neighborhood.