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1 **How is rockfall risk impacted by land-use and land-cover changes? Insights from the French Alps.**

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8

9 **Abstract**

10

11 Due to intense urban sprawl in rockfall-prone areas, a precise rockfall risk assessment has become a crucial issue
12 for public authorities and stakeholders. In this context, quantitative risk analysis (QRA) procedures, accounting for
13 the specificities of the rockfall process, have been developed. For the last few decades, several studies have
14 examined the impacts of global warming on rockfall activity, especially at high-altitude sites. However, the
15 influence of land-use and land-cover (LULC) changes, very frequent at lower altitudes and in the vicinity of
16 urbanised areas, on rockfall propagation and associated risks has received little attention.

17 This study proposes a holistic QRA on a municipality scale (the municipality of Crolles, in the French Alps) that
18 includes both all the potential release areas at the whole cliff scale and a wide spectrum of rockfall volumes
19 randomly extracted from volume classes distributed between 1 and 20 m³. In addition, to quantify precisely the
20 effect of LULC changes on rockfall risk, four characteristic scenarios representative of LULC changes observed in
21 the municipality and more generally in the Alps since the mid-19th century, have been included in the analysis.

22 The results demonstrate the significant impacts of landscape reorganisation on the spatial distribution of risk with
23 increasing forest cover, which can be counterbalanced by evolving LULC in a transition unit located between the
24 forest strip and the urban front. They also evidence that a large proportion of the risk is explained by small block
25 volumes, which are the most affected by landscape structure and evolution. From a practical point of view, and
26 despite several uncertainties related to different modelling assumptions, the results reported herein clearly
27 demonstrate the applicability and the value of QRA for rockfall risk management at a municipality scale in a
28 context of rapid and intense environmental changes.

29 **Keywords:** Land-use and land-cover changes; Rockfall risk; Quantitative Risk Analysis; Non-stationary process

30

31

32 **1. Introduction**

33

34 Rockfalls are widespread phenomena in mountainous regions, described as the free falling, bouncing and/or rolling
35 of individual rocks and boulders of different sizes originating from (sub)vertical cliffs (Varnes, 1978; Erismann and
36 Abele, 2001). They are triggered by multiple factors such as short-term weather conditions (freeze-thaw events,
37 temperature variations or intense precipitation), seismic activity, permafrost degradation, vegetation (root
38 wedging) or human activities (D'Amato et al., 2016; Noetzli, 2003). This multiplicity of triggering factors, the lack
39 of reliable precursor signals, the sudden occurrence of rockfalls as well as individual rock detachment (Hantz,
40 2013) result in a spatio-temporal unpredictability that endangers human lives, transportation infrastructure,
41 industry and housing. Abundant literature reports fatalities in Alpine environments, e.g., in Switzerland (Badoux et
42 al., 2016; Straub and Schubert, 2008), France (Assali, 2015), Italy (Agliardi et al., 2009) and Austria (Haque et al.,
43 2016). Rockfall protection through rigorous land-use planning based on hazard zoning maps and/or appropriate risk
44 mitigation measures is therefore a crucial issue for authorities and stakeholders in rockfall-prone areas (see e.g.
45 Agliardi et al., 2009; Corominas et al., 2005). Although hazard zoning is a useful tool for land planning, the design
46 and optimisation of both structural and non-structural protective countermeasures require precise risk analysis and
47 evaluation (Volkwein et al., 2011).

48 In that respect, quantitative risk assessment (QRA) procedures developed for landslides (Corominas et al., 2013;
49 Fell et al., 2005, 2008; Lari et al., 2014) have been adapted to account for the specificities of rockfall processes
50 (Agliardi et al., 2009; Corominas et al., 2013, 2005; Corominas and Mavrouli, 2013; Moos et al., 2017). They
51 classically include each term of the risk components in the form of probabilities and the estimation of probable
52 consequences, so that risk can be expressed in monetary value (Hackl et al., 2018). In addition, in the case of
53 rockfalls, they integrate 3D numerical models to evaluate the spatial probability and intensity of impacts on
54 structures (Agliardi et al., 2009). QRA differs from qualitative risk analysis by the input, the procedures used in the
55 analysis and the final risk output. In contrast with qualitative risk analysis, such as the Rockfall Hazard Rating
56 System (RHRS) (Budetta, 2004; Budetta and Nappi, 2013; Ferrari et al., 2016), which yields results in terms of
57 weighted indices, QRAs quantify the probability of a given level of loss. For society in general, QRAs help increase
58 the awareness of existing risk levels and the appreciation of the efficiency of the actions undertaken (Corominas et
59 al., 2013). However, in practice, the quantitative estimation of the different components of risk is challenging
60 (Corominas et al., 2005) due to the spatially distributed nature of rockfall processes, for which both the probability
61 of an impact on different elements at risk and intensity vary significantly along block trajectories. The challenge

62 also stems from the detailed data and/or economic resources required for these analyses (Ferrari et al., 2016). As a
63 consequence, the literature focusing on QRAs in rockfall-prone regions remains scarce (see Corominas et al., 2013,
64 for a review). QRAs are mostly site-specific (Ferrari et al., 2016) and restricted to critical release areas with a
65 retro-analysis of rockfalls involving a few blocks (Corominas et al., 2005; Agliardi et al., 2009). In addition, most of
66 these studies only consider a partial distribution of rockfall volumes and do not account for the spectrum of hazard
67 scenarios. More broadly, as for other natural hazards, classical rockfall risk evaluation procedures are defined
68 under stationary conditions, implying that events arise with a constant probability distribution over time. This
69 ignores possible rockfall activity variations related to environmental changes (Eckert et al., 2018). However, over
70 the last few decades mountain zones, where most rockfall risk is located, have experienced strong and rapid socio-
71 environmental mutations combined with the rapidly changing climate (e.g., Beniston et al., 2018). Since the
72 beginning of the last century, in European mountain regions (Kamada and Nakagoshi, 1997; Romero-Calcerrada and
73 Perry, 2004; Walther, 1986), the abandonment of traditional agriculture has produced vegetation succession
74 occurring at varying rates dependent on the site conditions. This process results in dense shrub cover and finally in
75 reforestation (Tasser and Tappeiner, 2002). In the vicinity of urban areas, this rapid agro-pastoral decline has been
76 followed by intense periurban expansion since the mid-20th century. Interactions and retroactions between natural
77 hazard processes, social practices, periurban sprawl and ecosystem changes are numerous (e.g., Field and
78 Intergovernmental Panel on Climate Change, 2012). This results in substantial changes in mountain risks,
79 potentially differing greatly from one area to another (e.g., Stoffel and Huggel, 2012). In the specific case of
80 rockfall, a few studies have documented an increase in high-altitude rockfall frequency related to global warming
81 and permafrost degradation (Einhorn et al., 2015; Noetzi, 2003; Ravelin and Deline, 2011). Yet, to our knowledge,
82 at lower altitudes and within a QRA approach, no study has integrated the evolution of landscape patterns that
83 potentially affect rockfall propagation and energy (Lopez-Saez et al., 2016). This lack of dynamical analyses
84 precludes reliable anticipation of rockfall risk in a context where environmental conditions are evolving rapidly and
85 substantially.

86 In contrast to previous studies restricted to the retro-analysis of a few critical release areas, we investigated here
87 a complete 3-km-long limestone cliff, located on the edge of the Isère Valley (French Alps), in the municipality of
88 Crolles, where (i) numerous rockfalls, (ii) an intense agro-pastoral decline and (iii) rapid periurbanisation - related
89 to the nearby Grenoble conurbation (500,000 inhabitants) - have been reported since the beginning of the 20th
90 century (Lopez-Saez et al., 2016). To quantify the impacts of land-use and land-cover (LULC) changes on rockfall
91 risk, we (i) determined a volume-frequency relationship for rockfall events at Crolles using an asymptotic model of
92 the generalised Pareto family, which better accounts for the frequency of extreme events than previously used

93 power-law approaches, through detailed historical/field observations; (ii) performed a quantitative risk analysis
94 simultaneously including all the release areas that potentially threaten the village as well as (iii) the whole
95 distribution of rockfall volumes randomly extracted in the range 1-20 m³; (iv) adapted a rockfall simulation model
96 to keep track of each simulated individual trajectory; (v) expressed the risk in m² destroyed per year at the level of
97 each individual building and (vi) compared the spatial risk distribution, the overall mean annual value at the scale
98 of the entire study area and the risk distribution among 19 equal volume classes for four characteristic LULC
99 patterns observed over the last 150 years at Crolles. These different LULC patterns, associated with the pre-
100 industrial, post-World-War II, urban sprawl and current periods in Crolles, can all still be encountered today on
101 south-facing slopes in the calcareous Alps.

102 Based on this approach, we propose a holistic QRA procedure where each risk component is precisely quantified.
103 The implementation of the four archetypal landscapes within the analysis contributes to the broader scope of the
104 results providing, for the first time, a risk analysis that takes into consideration non-stationary environmental
105 conditions.

106

107 2. Study site

108

109 The village of Crolles (45° 17'09"N, 5° 53'01"E) is located in the Isère department, northeast of the Grenoble
110 conurbation (Fig. 1A, B). It covers an area of 14.2 km² from the Bec Margain (1036 m a.s.l.) to the Isère River (220
111 m a.s.l.) (Fig. 1C). The village is settled on the eastern slope of the Chartreuse Massif (French Alps), with slope
112 angles that decrease gradually from 45-50° in its upper portion to 15° at the level of the urban front with a marked
113 concavity between 300 and 350 m a.s.l. It is topped by a 300-m-high sub-vertical cliff made of thick-bedded
114 limestones and marls from the upper Jurassic period (Dussauge-Peisser et al., 2002). The cliff triggers rockfall with
115 sizes varying from gravel clasts to blocks with volumes greater than 30 m³. Historical archives, fresh blocks, recent
116 impact craters on the ground and visible growth disturbances (i.e. scars, decapitated trees) on the forest stand
117 confirm ongoing numerous rockfalls released from the entire cliff section. Since the mid-20th century, the village
118 has experienced intense periurban expansion. Several neighbourhoods (Fagnès, Magny, Coteau, Ardillais) have
119 spread over the southeastern slopes of the Chartreuse Massif (Fig. 1C), and are therefore exposed to increasing
120 danger related to rockfall activity. As a consequence, since 1995 several protective walls have been constructed to
121 reduce rockfall risk and an additional 1-km-long dike will soon be finalised (Fig. 1C).

122 At Crolles, LULC patterns have undergone major changes since 1850 with a clear trend towards an increase in
123 forest cover and urban areas (Fig. 1D, E). In 1850, the slope was characterised by a quasi-binary landscape with (i)

124 vineyards occupying up to 28° slope gradients at altitudes below 450 m a.s.l. where a continuous forest strip then
125 took over to extend up to the base of the calcareous cliff (Fig. 1D). Urban and cultivated allotments are scattered
126 below 280 m a.s.l. but only cover spatially limited surfaces, typically on gentle slopes. For the period between
127 1850 and the 1950s, historical documents evidence a generalised abandonment of vineyards. A similar decline in
128 viticulture has been observed in alpine vineyards between 1880 and the 1970s and is related to (i) the generalised
129 agricultural decline after the First and Second World Wars, (ii) the phylloxera (*Phylloxera vastatrix*) outbreaks that
130 destroyed most vineyards in 1880-1890 (Stevenson, 1980; Veyret-Verner, 1937), (iii) the increasing competition
131 from wines from southeastern France and (iv) the disappearance of the Grenoble military market in 1925
132 (Grandvoininnet, 2011). Schematically speaking, downslope wine plots have been replaced by grasslands. The
133 upslope allotments were abandoned first and were either replaced with untilled land or colonised by the upcoming
134 forest. In the 1980s, the abandonment of agricultural plots and the spread of the forest continued to affect the
135 areas upslope of the main constructed areas. Finally, nowadays the landscape is characterised by a dense forest
136 cover on most of the slope and the presence of discontinuous grassland plots scattered among constructed and
137 wooded plots (see Lopez-Saez et al., 2016, for a detailed description). LULC changes are accompanied by a sharp
138 increase in the length of the urban front potentially exposed to rockfall controlled by the rapid expansion of the
139 Grenoble peri-alpine conurbation (Fig. 1E).

140 In this paper, we deliberately decided to disregard the urban development from our analysis in order to isolate the
141 impacts of landscape dynamics on the rockfall risk. This decision was also supported by the complexity of
142 evaluating exposed structures in the mid-19th century. For the same reasons, the risk calculation does not account
143 for the current protective walls. As a consequence, we decided to use four LULC maps obtained from the
144 diachronic landscape analysis performed in Lopez-Saez et al. (2016) as patterns roughly representing the pre-
145 industrial (hereafter referred to as the binary pattern), post-World-War II (mosaic A pattern), urban sprawl (mosaic
146 B pattern) and current (densely forested pattern) periods (Fig. 2). The urban front exposed to rockfalls was
147 delineated from the cadastral map and included in the quantitative risk analysis for each pattern.

148

149 **3. Risk framework and numerical model set-up**

150

151 **3.1 General framework and computation**

152

153 Risk is generally defined as a combination of the damageable phenomenon and its consequences (Eckert et al.,
 154 2012), thus describing a statistical value for the expected damage per year. By considering all the scenarios which
 155 characterise a risk situation, the rockfall risk can be expressed with the following integral:

$$R_w = \sum_{z \in w} q(z_w) z_w \int f(\text{Event}) p_z(\text{Event}) D_z(\text{Event}) d\text{Event} \quad (1)$$

157
 158 R_w represents the expectations of the consequences (or a certain amount of damage) of hazard activity for the
 159 whole system at risk, w . This system is composed of a set of any element or combination of elements z potentially
 160 at risk, characterised by an exposure factor $q(z_w)$ and a value z_w .

161 In the most common configurations, these elements are physical (i.e. people, traffic infrastructure, buildings), but
 162 other less tangible aspects can be introduced such as the image and aesthetics of an element (Eckert et al., 2012).

163 The frequency $f(\text{Event})$ of the hazard, the reach probability $p_z(\text{Event})$ on an element at risk z and the resulting
 164 damage $D_z(\text{Event})$ are derived for all possible events and are representative of physical and kinetic rockfall
 165 properties (i.e. volume, mass, shape, translational and rotational energies, passing height, impact angle, etc.).

166 Due to the complexity and suddenness of rockfall processes, several parameters that would be useful for risk
 167 assessment are systematically lacking (Bourrier et al., 2016; Eckert et al., 2012). A simplified approach in which
 168 only rock volumes and kinetic energies are included is generally adopted following the equation:

$$R_w = \sum_{z \in w} q(z_w) z_w \int f(v) \left[\int p_z(E|v) D_z(E) dE \right] dv \quad (2)$$

170 where $f(v)$ corresponds to the occurrence frequency of rockfall events with a volume v , $p_z(E|v)$ the reach
 171 probability on an element at risk z by a block of volume v with an energy E and $D_z(E)$ the resulting damage on z for
 172 an impact energy E .

173 Risk analysis is performed numerically on a case-by-case basis (Fig. 3) by distinguishing each element at risk z
 174 identified in the system w . The risk value specific to each element z is approximated by discrete sums on several
 175 volume classes. For each of these volume classes, the damaging value is evaluated by the Monte Carlo method as:

$$\bar{D}_z(V_{CL_i}) \approx \frac{1}{N} \sum_{k=1}^N D(z, E_k) \quad (3)$$

177

178 where $E_k \in [1, N]$ is the local distribution of rockfall energies evaluated over N simulations. Thus, the risk for the

179 element z is expressed as:

180

$$R_z = q(z_w) \times z_w \times \sum_{i=1}^l f(V_{CL_i}) \times p_z(V_{CL_i}) \times \bar{D}_z(V_{CL_i}) \quad (4)$$

181

182 where the volume distribution is discretised in V_{CL} classes.

183 Finally, the total risk for the system w is the sum of individual risks for each of the elements z (Eckert et al.,

184 2012), i.e.:

185

$$R_w = \sum_{z=1}^m R_z \quad (5)$$

186

187 3.2 Rockfall probability

188

189 In rockfall terminology, the rockfall hazard refers to the probability of an event (rockfall) of a given magnitude
190 (volume) or intensity (energy) over a predefined period of time and within a given area (see e.g. Varnes 1984,
191 Ferrari et al., 2016). This parameter involves both the spatial probability of occurrence (i.e. susceptibility) and the
192 related temporal probability, which is also called the probability of failure (i.e. frequency).

193 Susceptibility is the likelihood that a block departure event will occur in a specific area based on the local terrain
194 conditions (Brabb, 1984). Previous studies mostly used release points of historical rockfall events or
195 geological/geostructural/geophysical approaches (characterisation of discontinuities and failures, photogrammetry,
196 terrestrial laser scanning, microseismic monitoring; Assali, 2015; Budetta, 2004) to detect and map rock
197 instabilities. These approaches are usable for small-scale sites but are not suitable for larger-scale approaches.

198 Given that gravity is the main driving force acting on slopes and that it is directly proportional to the inclination
199 (Loye et al., 2009), the morphology of a terrain displays characteristic slope angles that can be directly related to
200 morphological units (such as rock cliffs, steep slopes, foot slopes and plains). In this study, we applied a DEM-based
201 geomorphometric approach known as the slope angle frequency distribution (SAFD) procedure (Loye et al., 2009;
202 Michoud et al., 2012) to detect rockfall release areas at the whole-cliff scale. In this procedure, using the Excel-

203 based Histofit application, slope angle distribution is decomposed in several Gaussian distributions. The terrain is
 204 considered a potential rockfall source if its slope angle exceeds a certain threshold, which in turn is defined where
 205 the Gaussian distribution of the “rock cliff” morphological unit becomes dominant over the “steep slope” unit.
 206 In addition to susceptibility, the temporal probability of failure must be addressed to define the probability of the
 207 occurrence of a rockfall event, expressed in terms of frequencies or return periods (Ferrari et al., 2016). In this
 208 study, the temporal probability of a rockfall with a given volume was evaluated through a return rockfall-frequency
 209 procedure (De Biagi et al., 2017), which investigates historical events to (i) describe the temporal occurrence of
 210 the events and (ii) describe the rockfall volume distribution. For this purpose, 29 blocks with volumes ranging from
 211 0.2 m³ to 10 m³ were inventoried along a 900-m-long transect located in the Ardillais neighbourhood (Fig. 1C).
 212 Statistical modelling of extreme values has now emerged as an important statistical discipline that aims at
 213 generically quantifying the stochastic behaviour of extreme events (Coles, 2001). Here, by contrast with previous
 214 studies where a power-law approach was used (Dussauge-Peisser et al., 2002; Lopez-Saez et al., 2016), we adopted
 215 an asymptotic model from the generalised Pareto distribution (GPD) family to characterise the distribution of
 216 volumes exceeding a volume threshold value u . According to Pickands (1975), for any random variable, this is the
 217 true limiting distribution as soon as u is high enough. In this study, the threshold $u = 1 \text{ m}^3$ was used because we
 218 consider it the minimum volume that can significantly damage buildings. Finally, a catalogue containing only the
 219 volumes u and greater was retained from field observations. Given an estimated observation period evaluated at
 220 100 years (see Results section), this catalogue is used to estimate the temporal occurrence frequency of the events
 221 ($\hat{\lambda}$) and the local estimates for the GPD model. The annual cumulative distribution of rockfall volumes (Fig. 4) is
 222 then given by:

223

$$f(V > v | u) = \hat{\lambda} \times \text{GPD}(\hat{\sigma}, \hat{\xi}) = \hat{\lambda} \times \left[1 + \hat{\xi} \left(\frac{v - u}{\hat{\sigma}} \right) \right]^{-1/\hat{\xi}} \quad (6)$$

224 where V represents the volume of the blocks (in m³), $\hat{\lambda}$ is the temporal occurrence frequency of rockfall per unit of
 225 area (events/yr/hm²), and u , $\hat{\sigma}$, $\hat{\xi}$ the location, scale and shape of the GPD distribution, respectively. The
 226 circumflex denotes statistical estimates obtained from the data using a maximum likelihood procedure.

227

228 3.3. Trajectory and maximum runout of falling blocks

229

230 Due to the scattering of the rockfall phenomenon, the propagation component must also be taken into account in
231 rockfall hazard assessments (Crosta and Agliardi, 2003).

232 The proportion of risk analysis involving the interaction between rockfalls and elements at risk (i.e. impact
233 probability and vulnerability) was supported by high-resolution 3D numerical modelling performed using the
234 Rockyfor3D (v5.0) code (Dorren, 2012). On the basis of a digital elevation model, this probabilistic process-based
235 rockfall trajectory model combines physically based deterministic algorithms with stochastic approaches to
236 simulate rockfall in three dimensions. The model calculates sequences of classical, uniformly accelerated parabolic
237 freefall through the air and rebounds on the slope surface and trees (for details see Dorren et al., 2005). During
238 each rebound, the model allows the block to deviate from its direction before rebounding. If an impact against a
239 tree takes place, part of the rock energy is dissipated as a function of the stem diameter of the corresponding tree
240 and the relative position between the rock and tree center. LULC patchiness is explicitly integrated into
241 Rockyfor3D through its spatial modelling features. The parameters used to characterise the interactions between
242 the block and the soil - soil mechanical properties (i.e. restitution coefficients) and soil roughness - are implicitly
243 related to LULC patterns. As outputs, the model provides, for example, information on rock propagation for any
244 location in the study site such as the number, in the simulation sample, of passing rocks through a given surface or
245 the mean of the maximum kinetic energy values of all simulated blocks in a given location.

246 In the transit area, Rockyfor3D uses a normal and a tangential coefficient of restitution to calculate rock rebound
247 on the slope surface (Volkwein et al., 2011). The normal coefficient of restitution (r_n) defines the change in normal
248 velocity during impact. In Rockyfor3D, r_n values are associated with slope materials depending on mechanical
249 properties, i.e. the capacity of slope materials to dissipate energy. The tangential coefficient of restitution (r_t)
250 defines the reduction in tangential velocity during impact. Both coefficients depend on (i) the rock shape and
251 radius and (ii) the depth of the impact crater during a rebound (Dorren et al., 2005). Given that the composition
252 and size of the material covering the slope surface and normal restitution coefficients are closely related to land
253 use, they were translated into several LULC classes (Table 1; Table 2). The oldest forest allotments present in the
254 upper part of the slopes, at the contact with the cliff, were mainly located on steep scree slopes. These forests
255 have been assigned high surface roughness values (Rg10: 0.25 m; Rg20: 0.15 m; Rg70: 0.05 m). In contrast, limited
256 roughness (Rg10: ≤ 0.05 m; Rg20: 0.0 m; Rg70: 0.0 m) was associated with cultivated land (i.e. grassland, farmland
257 allotments) and urbanised areas. Finally, the protective walls were removed from the DEM and gaps were corrected
258 using a spatial interpolation method.

259

260 3.4. Reach probability, mean damage and elements at risk

261
 262 Quantitative risk assessment was performed for the four land-use and land-cover maps introduced above. This
 263 study does not account for rockfalls with volumes that exceed 20 m³ so as to (i) preserve the efficiency of data
 264 storage and processing as well as to (ii) remain within the Rockyfor3D model validity range. Rockfall cell sources
 265 defined through the slope angle frequency distribution approach were mapped on the DEM and 10 000 rockfalls
 266 with volumes randomly extracted between 1 and 20 m³ were simulated from each source cell. For each landscape
 267 pattern, the elements at risk considered in the analysis include the buildings currently existing in the Crolles urban
 268 map (Fig. 1C). In Rockyfor3D the latter are characterised as obstacles with infinite height and resistance. As a
 269 consequence, in case of any impact with an element at risk, each block is stopped. The original source code of
 270 Rockyfor3D was modified to enable the storage, for each simulation, of (i) the building reached, (ii) starting cell
 271 IDs, (iii) the volume of the block and (iv) its kinetic energy (in kJ). The results are recorded in a database used
 272 subsequently to compute the probability of an impact on the elements at risk z as:

$$p_z(V_{CL}) = \frac{\text{Sim}_z(V_{CL})}{\text{Sim}_{\text{Tot}}(V_{CL})} \quad (7)$$

273
 274 where $p_z(V_{CL})$ is the reach probability on element at risk z for blocks belonging to the volume class V_{CL} . $\text{Sim}_z(V_{CL})$ is
 275 the total number of blocks simulated in the volume class V_{CL} that reach the element at risk z and $\text{Sim}_{\text{Tot}}(V_{CL})$ is the
 276 total number of blocks simulated in the volume class V_{CL} .

277 Impact energies recorded over the simulations which impact an element at risk were expressed as a damaging
 278 value on a structure. Considering that all the houses in Crolles were constructed using similar materials (e.g.
 279 masonry or reinforced concrete framing), damage values were obtained from the physical vulnerability curve of
 280 Agliardi et al. (2009), which derives the energy of impact as a potential degree of loss evolving between 0 (no
 281 structural damage) and 1 (total collapse). This curve results from the back-analysis of the 2004 rockfall event in
 282 Fiumelatte (Italy). It combines observed damage on structures and computed impact energies (through the HY-
 283 STONE code). Since an element at risk can be reached by a large number of simulations in a given volume class V_{CL} ,
 284 its damage value is set by the mean of the distribution as following:

$$\overline{D}_z(V_{CL}) = \frac{1}{k} \sum_{k \in V_{CL}}^n 1 - \frac{1.358}{1 + e^{\frac{E_k - 129000}{120300}}} \quad (8)$$

286
287 where $\overline{D}_z(V_{CL})$ is the mean damage on element at risk z for blocks belonging to the volume class V_{CL} , and E_k is the
288 impacted energy (in kJ) for the block belonging to the V_{CL} class.
289 Contrary to vehicles, trains and humans, buildings are static and consequently exposure factor $q(z_w) = 1$. Finally,
290 the values z_w are defined as the floor area (m^2) approximated from the current cadastral map. The risk is thus
291 expressed as the mean surface destroyed each year (m^2/yr).

292 293 **4. Results**

294 295 4.1. Rockfall frequency and release areas

296
297 The fitted generalised Pareto model is characterised by maximum likelihood estimators $\hat{\theta}$ and $\hat{\xi}$ equal to 0.94 and
298 0.355, respectively (Fig. 4). The related uncertainty is obtained by propagating the maximum likelihood estimation
299 asymptotic covariance matrix of the estimates using a delta-like approach. Based on the relative freshness of the
300 blocks (limited patina, absence of blunt or rounded-off edges, lichens or vegetation on the surface) and the
301 presence of visible scars on tree stems, we estimated that the reference period for the computation of rock
302 frequency should not reasonably exceed one century. Based on this estimated timeframe, we inventoried 17 blocks
303 greater than $1 m^3$ potentially released from a 11.5-hm^2 cliff section located above the representative transect
304 chosen for field analysis. As a consequence, the rockfall frequency $\hat{\lambda}$ was estimated at $0.015 \text{ events/yr/hm}^2$.
305 According to the Histofit routine, the threshold slope angle for source areas was set at 49° and 20 331 cells were
306 identified as potential rockfall release areas. These sources were evaluated to correspond to a total surface of
307 127.85 hm^2 , and consequently the frequency of rockfalls greater than $1 m^3$ and $20 m^3$ were estimated at 1.89 and
308 0.005 events/yr, respectively. Last, since a limited distribution (up to $20 m^3$) was considered, the frequencies per
309 volume class $f(V_{CL})$ were normalised by $\int_{20}^{\infty} \text{GPD}(\hat{\theta}, \hat{\xi})$ to obtain a probability density function with a total probability
310 of one.

311 312 4.2. Probability and energy of rockfall impacts

313

314 The database obtained from the rockfall simulations was used to estimate probabilities and energies of rockfall
315 impacts. These were interpreted at the level of each individual house as well as at the municipality scale (i.e.
316 regardless of the single elements at risk), for all the volume classes or in specific volume ranges.

317 In the binary pattern, the landscape is characterised by a continuous forest strip at the base of the cliff and the
318 presence of vineyards below 450 m a.s.l. (Fig. 2A). At the municipality scale, and regardless of the volume class, 1
319 115 111 impacts, homogeneously distributed at the scale of the urban front, were recorded on 342 buildings (Fig.
320 5A). A total of 96% of the impacted buildings had an individual reach probability (p_z) below 0.01% while p_z never
321 exceed 0.05% (Table 3). The impacts were not restricted to the upper portion of the urban front, but blocks passing
322 in the intervals between houses reached the sixth row of buildings in, for example, the Coteau neighbourhood (Fig.
323 5A). In addition, the kinematic energies exceeded 1000 kJ for 85% of the impacts and are typically associated with
324 volumes greater than 10m³.

325 In the mosaic A pattern, despite the widening of the forest strip on the upper part of the slope (from 36 to 51% of
326 the total surface) (Fig. 2B), the number of blocks that reached the urban front was multiplied by almost 10. In
327 contrast, the 11 320 596 impacts were distributed over a more limited number of buildings (263) (Fig. 5B). The
328 individual reach probability p_z exceeded 0.05 for 19 (7%) elements at risk (Table 3). Overall, the impact energies
329 were lower and did not exceed 1000 kJ for 61% of the impacts.

330 The mosaic B pattern differed from mosaic A in its limited afforestation (+6%) (Fig. 2C), but the density of the
331 forest stand in Rockyfor3D increased from 1000 to 1500 trees/ha (Table 2). This change in the forest stand
332 structure induced a sharp decrease in the total number of impacts (1 267 674). The number of impacted buildings
333 remained stable (260) (Fig. 5C), yet p_z exceeded 0.05% for three buildings that concentrated 35% of the total
334 number of simulated impacts. Energies greater than 1000 kJ accounted for 66% of the impacts.

335 Finally, in the last pattern implemented in rockfor3D - representative of the current landscape at Crolles (Fig. 2D) -
336 1 645 834 impacts were recorded on 177 buildings (Fig. 5D). The impacts were restricted to the first two rows of
337 exposed buildings. In total, 92% of the impacted elements at risk had a reach probability p_z less than 0.01%, but
338 two buildings located in the Coteau neighbourhood were characterised by a p_z value greater than 0.05%.

339 Interestingly, they accounted for 10 and 42% of the total number of recorded impacts, respectively. The increase of
340 forest coverage (+11% wrt mosaic B pattern) induced a substantial dissipation of block energies, with only 41% of
341 impacts exceeding 1000 kJ at the level of the urban front.

342 Maximum energies of 78 400 kJ (block volume, 20 m³), 70 700 kJ (block volume, 19 m³), 75 300 kJ (block volume,
343 20 m³) and 66 400 kJ (block volume, 18 m³) were recorded for the binary, mosaic A, mosaic B and densely forested
344 patterns, respectively.

345
346 4.3. Vulnerability and risk analysis results
347
348 The energies of rockfall impacts at the level of each element at risk were converted to an expected damage level
349 based on the empirical vulnerability function developed by Agliardi et al. (2009). In the binary pattern, the means
350 of the damage distribution of volume classes above 5 m³ were always higher than 0.9. For smaller volumes,
351 distributions were more scattered (Fig. 6), but the mean damage values remained above 0.8 regardless of the
352 volume class. In the mosaic A pattern, the energy of the blocks that reached the urban front was considerably
353 reduced irrespective of the volume. Comparing the binary and mosaic A patterns, the mean damage induced by
354 blocks whose volume was in the classes 1-2, 5-6, 10-11 m³, for example, decreased from 0.8 to 0.3, 0.9 to 0.5 and
355 0.9 to 0.75, respectively. In mosaic B, the mean damage value (0.75) for 1- to 2-m³ blocks was comparable to the
356 binary pattern and varied between 0.8 and 0.9 for volume classes above 2 m³ (Fig. 6). Finally, in the densely
357 forested pattern, despite the lower number of blocks that reached the urban front, the mean damage was greater
358 than in mosaic A for volume classes up to 7 m³. Conversely, the energies of the largest class volumes were lower in
359 the densely forested pattern, the mean damage decreasing from, for example, 0.75 to 0.6 and 0.9 to 0.8 for the
360 volume classes 10-11 m³ and 19-20 m³, respectively.

361 Following Eq4 and Eq5 - which combine the rockfall frequency, the individual reach probability and the mean
362 degree of loss of each element at risk, for each volume class (Fig. 3) - we computed the risk to buildings in terms
363 of mean annual destroyed surface per year (m²/yr). Following this approach, the mean total risk R_w decreased from
364 0.2 to 0.1 m²/year between the binary and the densely forested patterns. Despite the progressive afforestation of
365 the slope (from 36 to 68%), it should be stressed that the risk did not decrease linearly. Mosaic patterns A and B
366 were characterised by destroyed surfaces ten times greater than (1.1 m²/yr) and similar to the binary pattern (0.2
367 m²/yr), respectively. In detail, the individual risk was less than 0.001 m²/yr for the vast majority of the impacted
368 buildings for each pattern (Fig. 5). If we consider a typical structure of 150 m², this value corresponds to the
369 complete destruction of the building every 150 000 years. On the other hand, it exceeds 0.01 m²/yr for 5, 21, 4 and
370 1 buildings for the binary, mosaic A, mosaic B and densely forested patterns, respectively, but the location of these
371 most impacted elements changes depending on landscape patterns (Fig. 5).

372 Figure 7 shows the risk for each pattern depending on the 19 volume classes. Each distribution is compared with
373 the expected risk value when the degree of loss is set at a value of 1. With the exception of volume classes less
374 than 2 m³, both distributions collapsed for binary and mosaic B patterns. Conversely, for the mosaic A and densely
375 forested patterns, the discrepancies between the two distributions induced a difference of 38 and 35% in the

376 rockfall risk, respectively. These differences illustrate the influence of energy on the risk, namely the ability of
377 masonry walls to resist “low” energy impacts.

378 In addition, for all the patterns, the distributions of risk with maximum and mean degrees of loss presented a single
379 peak. This peak was observed for similar volume classes (2-3 m³) for the binary and mosaic B patterns, whereas
380 they occurred for volume classes 8-9 and 10-11 m³ in the case of binary and densely forested patterns,
381 respectively. The shift of these peaks from 1-2 m³ to higher values evidences the non-linear relationship between
382 reach probabilities and volumes directly related to the influence of landscape structures.

383

384 5. Discussion

385

386 5.1. Impacts of landscape organisation on rockfall risk

387

388 In this study, we developed a quantitative analysis of rockfall risk in the municipality of Crolles (French Alps). To
389 integrate a wide spectrum of probability of occurrence, propagation, intensity, impact probability and resulting
390 damage to buildings, the complete distribution of block volumes in the range 1-20 m³ was implemented in our
391 rockfall risk calculation. Applied to four LULC patterns representative of the landscape observed on south-facing
392 calcareous slopes in several alpine valleys, this provides a better understanding of the interactions between the
393 landscape structure and the rockfall risk. The results were presented at the level of each building and at the
394 municipality scale, in order to map the most risk-prone areas and to identify the impacts of LULC changes on the
395 overall risk, respectively. Unsurprisingly, these results demonstrate that the risk was reduced by a factor of 2 as a
396 result of the intense afforestation process observed between the binary and densely forested patterns (+32%). This
397 reduction is attributed to forest-block interactions that significantly reduce both the reach probability and the
398 energy of rockfalls (Dupire et al., 2016a; Dupire et al., 2016b; Toe et al., 2018). In the densely forested pattern,
399 our analysis demonstrates that the high and dense forest cover has a significant influence on rockfall risk
400 associated with lower volumes, but its protective function is limited for rock volumes greater than 10 m³. These
401 results are consistent with the findings of Moos et al. (2017) at two sites in the Swiss Alps, demonstrating that risk
402 is strongly reduced (between 20 and 50%) in forest areas for volumes less than 5 m³ but can remain considerable for
403 greater volumes when forested slopes are sufficiently long. On a spatial plan, the comparison of risk maps shows (i)
404 changing distributions of exposed buildings for each pattern and (ii) a risk limited to the first exposed buildings in
405 the densely forested pattern. In greater detail, the existence of critical risk-prone areas in the densely forested
406 pattern seems to result from specific terrain conditions and LULC patterns, as observed in the Coteau

407 neighbourhood where the most impacted building (42% of reach probability, 27% of the total risk) is overhung by a
408 grassland plot located downslope from a preferential corridor (Fig. 8). To a certain extent, these results validate
409 the observations on virtual slopes that have shown the importance of forest fragmentation on the reduction of
410 rockfall intensity and, more specifically, demonstrated that the kinetic energies of blocks are significantly higher in
411 forest stands with a clustered tree structure and in forests with gaps or aisles compared to random tree distribution
412 (Dupire et al., 2016b; Toe et al., 2018).

413 More interestingly, despite a wider and denser forest strip, the risk does not decrease gradually and is, for
414 example, ten times greater in mosaic A than in the binary pattern. We hypothesise that this paradoxical evolution
415 is mainly driven by the evolution of soil mechanical properties implemented in Rockyfor3D, with vineyards
416 ($R_{g10}=0.10$, $R_{g20}=0.05$, $R_{g70}=0$, $R_n=0.23$) more likely to stop or decelerate blocks and to reduce their energy than
417 grassland characterised by an absence of roughness and larger normal restitution coefficients ($R_n=0.28$; Table 1).
418 This hypothesis is further supported by the propagation maps for the binary pattern showing the large proportion of
419 rockfalls stopped in the vineyard allotments (above 300 m a.s.l.). The protection function of the forest should not
420 be underestimated in the mosaic A pattern since we demonstrated its impacts on propagation for lower volume
421 classes (Fig. 7). Yet, the expansion of the forest strip remains insufficient to compensate for the loss of roughness
422 stemming from grassland expansion.

423 Finally, for mosaic B, R_w is (i) comparable to the binary pattern, but the risk is less diffuse on the urban front and
424 clustered in a limited number of risk-prone areas and (ii) considerably lower than mosaic A despite limited
425 differences in LULC patterns. These discrepancies could be explained by the expansion of wood formation (forest
426 and untilled land) on grassland and concomitant increasing roughness in the most concave portion of the slope
427 (Lopez-Saez et al., 2016) and to a lesser extent the increase in forest density.

428 All in all, these results suggest a key role played by the landscape structure and the associated roughness on
429 rockfall risk, especially with respect to low-volume/high-frequency classes, and clearly evidence that the risk
430 reduction associated with continuous afforestation can be significantly counterbalanced by landscape
431 reorganisation below the forest front. Similar effects of LULC changes have been reported for snow avalanche risk
432 (García-Hernández et al., 2017). By contrast, the scarce existing literature devoted to the non-stationarity of
433 rockfall processes mainly focuses on recent high-altitude changes under climate warming (e.g. Raveland and Deline,
434 2011). By focusing on LULC changes and explicitly quantifying the risk at a lower-altitude location where the
435 population is rapidly increasing, our results complement the current knowledge and broaden the perspective,
436 opening the door to the assessment of the complete response of a complex system to substantial simultaneous
437 physical, environmental and societal changes.

438
439 5.2. Novelty and limitations of the quantitative risk analysis approach undertaken at Crolles
440
441 Rockfall risk studies are usually based on the retro-analysis of rockfall events (Agliardi et al., 2009) to implement a
442 restricted number of rockfall volumes released from critical areas. Here, in order to propose a more holistic risk
443 analysis, we considered all the release areas that potentially threaten the village studied as well as the complete
444 distribution of rockfall volumes ranging from 1 to 20 m³. In addition, a power-law approach is commonly used to
445 characterise rockfall frequencies (Dussauge-Peisser et al., 2002; Lopez-Saez et al., 2016). By contrast, we used a
446 volume-cumulative frequency relationship fitted by an asymptotic model of the generalised Pareto distribution.
447 This approach has been demonstrated to be more suitable to quantifying the stochastic behaviour of numerous
448 occurrences of any process in a generic way (Coles, 2001), especially in the context of natural hazard assessment
449 (e.g. Evin et al., 2018; Favier et al., 2016). For each building, risk maps resulting from our analyses characterise a
450 probability of physical losses due to rockfalls. Furthermore, the implementation of the complete spectra of rockfall
451 volumes in our QRA procedure provides a robust understanding of the risk distribution associated with each volume
452 class. This approach is of major interest for stakeholders in charge of risk management because it allows for
453 prioritising and designing mitigation measures (Corominas et al., 2013, 2005). In addition, and in contrast to the
454 current practices in which risk is usually expressed as damage in monetary values (Agliardi et al., 2009; Moos et al.,
455 2017), we deliberately quantified the risk as a physical loss expressed in m²/yr. The choice of this metric -
456 independent of the spatial and temporal variability of the property prices - also guarantees the reproducibility of
457 the procedure and facilitates site-by-site comparison. Finally, the implementation of LULC patterns in this analysis
458 made it possible to document the impacts of landscape evolution on rockfall risk and ensures its replicability to a
459 wide range of calcareous south-facing slopes in the Alps. The use of realistic landscape scenario changes allows
460 rockfall risk analyses to be performed in a non-stationary context, which are urgently needed given the quick and
461 consequential changes now affecting the environment in which mountain hazards arise (Beniston et al., 2018;
462 Giacona et al., 2018). It could also be used in further work for a precise monetisation of ecosystem services, most
463 particularly those related to the protective function of different landscape patterns.
464 Despite its high interest for stakeholders, one must keep in mind that our methodology is based on several
465 assumptions inherent to quantitative risk analyses (Straub and Schubert, 2008) and related to (i) the magnitude and
466 frequency of rockfall, (ii) rockfall propagation and (iii) the scarcity of vulnerability relations in the existing
467 literature. With regard to the frequency distribution of rockfall volumes, the lack of a statistically representative
468 catalogue of rockfall events has been overcome at Crolles through detailed field observations along a

469 representative transect. Despite exhaustive field investigations, inaccuracies remain in this rockfall catalogue due
470 to (i) highly probable rock removal in the lower part of the slope and (ii) potential biases on the volume and
471 frequency estimations related to potential fragmentation during rockfall propagation (Corominas and Mavrouli,
472 2013). Regarding rockfall propagation (Bourrier et al., 2009), technical restrictions concern the ability of the
473 Rockyfor3D simulation model to properly simulate rockfall trajectories for large volumes. Furthermore, soil
474 mechanical properties attributed to each of the allotments remain difficult to estimate and the results reported
475 herein, in agreement with Corona et al. (2017), demonstrate that slight variations in roughness parameters in the
476 rockfall simulation model induce significant changes in energy loss and runout distance. Finally, damage
477 assessment is based on the vulnerability function specifically developed by Agliardi et al. (2009) for the Fiumelatte
478 (Italy) site. The choice of this function was driven by (i) comparable slope lengths (>500 m) and rockfall volume
479 classes at Crolles and Fiumelatte, (ii) the lack of damaging events at Crolles that would have enabled a site-
480 specific retro-analysis and (iii) the scarcity of vulnerability curves for structural elements in the existing literature.
481 For example, the approach developed by Mavrouli and Corominas (2010), which accounts for the impact location of
482 the rock and requires detailed information on the structure, was not applicable at our study site scale. Yet, the
483 results should be considered cautiously because (i) the vulnerability curve of Agliardi et al. (2009) was calibrated
484 on a limited number of documented events and (ii) it is impossible to precisely evaluate the relevance of this
485 transposition. In view of these different limitations, the risk values obtained in this study can be considered
486 indicative (Corominas et al., 2013), but further work is certainly required to evaluate the weight of the different
487 assumptions made on the final risk estimates. Specifically, a systematic quantification of uncertainties associated
488 with each of the risk components would greatly improve the reliability of the results (Straub and Schubert, 2008;
489 Wang et al., 2014).

490

491 **Conclusion and outlooks**

492

493 In this study, we developed a quantitative analysis of rockfall risk in Crolles that integrates (i) four different land-
494 use and land-cover patterns representative of observed landscapes on calcareous slopes in different periurban
495 regions in the Alps, (ii) the complete distributions of rock volumes in the 1-to 20-m³ range and (iii) all potential
496 release areas in order to assess the risk for a wide spectrum of patterns at the level of the current urban front. As
497 expected, the risk decreased significantly as the afforestation of the slope increased. Yet, we demonstrated that
498 the risk decrease is not gradual and that the positive effect of increasing forest cover can be strongly
499 counterbalanced by landscape reorganisation (e.g. vineyard replaced with grassland) in the transition area located

500 between the forest and the urban front. In addition, the approach developed here, at the municipality scale, not
501 only precisely maps the elements highly subjected to risk, but also evidences significant changes in the risk
502 patterns for different landscapes. These results, transposable to a wide range of calcareous south-facing slopes in
503 the Alps, can quantify the protection value of the landscape. They also demonstrate the added value of a dynamic
504 approach accounting for LULC changes for risk assessment. In the future, a similar procedure that would integrate
505 socio-economic evolution such as urban sprawl is encouraged and would provide a complete and more reliable risk
506 analysis. Finally, an additional key finding of the present study is that the evolution in rockfall risk is mainly driven
507 by lower-volume classes. This result carried even greater interest in that for these volume classes both frequency
508 and propagation could be potentially greatly affected by ongoing environmental changes in alpine regions (land
509 abandonment) as well as global warming. Although the limitations mentioned in the Discussion should be kept in
510 mind, they clearly demonstrate the practicability of the QRA at a municipality scale and its major value in terms of
511 risk zoning in a context of significant and rapid socio-environmental change.

512

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514

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714 **Fig. 1.** (A-B) The pre-alpine conurbation of Crolles is located in the Isère valley, near the city of Grenoble, on the
715 southeastern slopes of the Chartreuse Massif (French Alps); (C) General view of Crolles and the potential rockfall
716 release areas. The urban plan is divided into four neighbourhoods, namely Le Fragnès, Magny, Ardillais and Le
717 Coteau; (D-E) Historical photograph of Lumbin talus slope (close neighbour of Crolles) in 1911 (D) and a current
718 photograph of the talus slope in 2017 (E).

719
720 **Fig. 2.** Land-use and land-cover (LULC) maps of the Crolles slopes for the binary pattern, the mosaic A pattern, the
721 mosaic B pattern and the densely forested pattern.

722
723 **Fig. 3.** General scheme of the framework used to quantify the rockfall risk with regards to the volume class V_{CL} .
724 The methodology is summarised in five main steps: (1) estimating the rockfall frequency in class V_{CL} according to the
725 adopted volume-cumulative frequency relationship, (2) rockfall propagation through the Rockyfor3D code, (3)
726 calculating the reach probability p_z on each element at risk z related to volume class V_{CL} , (4) converting the related
727 impact energies as a degree of loss to determine the mean damage for the element z and (5) assess the risk as the
728 mean surface destroyed each year by integrating the raster surface. Total risk is obtained by an additional
729 summation over the different volume classes.

730
731 **Fig. 4.** Volume-cumulative frequency relationship in events/yr/hm² (red line) obtained by an asymptotic model of
732 the generalised Pareto distribution (GPD) family and related to rock volumes inventoried along a transect located
733 in the Ardillais neighbourhood. The shaded area illustrates the model 95% confidence interval.

734
735 **Fig. 5.** Distribution of the rockfall risk (m²/yr) at Crolles for the binary and the mosaic A patterns.

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737 **Fig. 5. (Continued)** Distribution of the rockfall risk (m²/yr) at Crolles for the mosaic B and densely forested
738 patterns.

739
740 **Fig. 6.** Density function of the damage for each pattern and block volumes in the range of volumes 1-2 m³, 2-3 m³,
741 3-4 m³, 4-5 m³.

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743 **Fig. 7.** Distribution of the rockfall risk in the 19 volume classes and for each landscape pattern. Each distribution is
744 compared with the risk distribution when the physical vulnerability is set at a value of 1 (total destruction of the
745 building as soon as it is hit, red line).

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747 **Fig. 8.** (A) Estimation of the reach probabilities on buildings of Le Coteau from Rockyfor3D numerical modelling
748 results and for the densely forested pattern. These results are mapped on the aerial picture of the area (B) to
749 evidence specific terrain conditions (grassland plot located downslope of a preferential couloir).

LULC type	Rg70	Rg20	Rg10	R _n	
Cliff	0	0	0.05	0.53	
Scree	0.1	0.2	0.35	0.38	
Vineyard	0	0.05	0.1	0.23	
Crops	0	0	0.05	0.28	
Grassland	0	0	0	0.28	
Thalweg	0.25	0.5	0.7	0.38	
Vegetated thalweg	0.25	0.5	0.7	0.28	
Wasteland	0.05	0.1	0.1	0.28	
Historical forest	0.05	0.15	0.25	0.33	
Forest	Mosaic patterns A and B	0.05	0.1	0.2	0.33
	Densely forested pattern	0.05	0.15	0.25	0.33

Table 1. LULC and related soil characteristics implemented in Rockyfor3D. Rg70, Rg20 and Rg10 correspond to the slope surface roughness (obstacles for the falling block lying on the slope) for 70%, 20% and 10% of the surface, respectively. R_n value (normal coefficient of restitution) defines the change in normal velocity during impact and is associated with the different soil types (Dorren, 2012).

LULC type	Pattern	Nb.trees.ha	DBH mean	DBH std
Scree	All	400	5	2
Vegetated thalweg / wasteland	Binary	200	10	5
	Mosaic A, mosaic B and densely forested	400	10	5
Historical forest	Binary	750	20	10
	Mosaic A, mosaic B and densely forested	3000	5	2
Forest	Mosaic A	1000	20	10
	Mosaic B and densely forested	1500	20	10

Table 2. LULC types and related tree cover implemented in Rockyfor3D. Nb.trees.ha values correspond to the density of trees (number of stems per hectare). Mean diameter of trees and associated standard deviation are described by DBH mean and DBH std values, respectively. Based on these values, the Rockyfor3D model randomly placed a given number of trees within each of the covered allotments (Dorren, 2012).

Nb _{TOT} houses reached	Pattern			
	Binary	Mosaic A	Mosaic B	Densely forested
	342	263	260	177
$p_z < 0.01\%$	328 (96%)	217 (83%)	244 (94%)	163 (92%)
$0.01\% \leq p_z < 0.05\%$	14 (4%)	27 (10%)	13 (5%)	12 (7%)
$0.05\% \leq p_z < 0.1\%$	0 (0%)	8 (3%)	3 (1%)	1 (0.5%)
$p_z \geq 0.1\%$	0 (0%)	11 (4%)	0 (0%)	1 (0.5%)

Table 3. Descriptive statistics of the number of houses impacted from Rockyfor3D simulations and reported in four reach probability classes (regardless of the volume class) for the four LULC patterns considered.

















