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1 **Assessment of the recurrence intervals of rockfall through dendrogeomorphology and counting**
2 **scar approach: a comparative study in a mixed forest stand from the Vercors massif (French Alps).**

3

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13

14 **Keywords** : *Rockfalls, Recurrence interval, Tree-ring analyses, French Alps*

15 **Abstract**

16 As direct observations of rockfalls are rare and difficult to obtain over long timescales, stem injuries and their
17 dating with dendrogeomorphic techniques have been applied frequently in the past to reconstruct process
18 activity. However, the analysis of tree-ring samples requires considerable temporal efforts, which can be
19 detrimental in applied research and expert opinions. To compensate for this shortcoming, several studies have
20 lately explored the potential of the counting of visible scars as an alternative method to dendrogeomorphology
21 as it requires much less time and human efforts to reconstruct spatial patterns of rockfall activity. Yet, to date,
22 both approaches have not been compared at the same site. In this paper, based on the extensive analysis of 278
23 conifer and broadleaved trees (from which 1097 tree-ring cores were extracted) from a mixed forest plot of the
24 Vercors Massif (French Alps), we demonstrate that both methods provide similar spatial patterns of rockfall
25 activity with a strong increase of recurrence intervals down the talus slope and a clear lateral zonation of
26 activity. Despite this apparent convergence between both approaches, our study also evidences that rockfall
27 frequencies strongly differ with tree species and diameter: the visual inspection of conifer stems and the analysis

28 of tree-ring signals in large-diameter broadleaved trees typically lead to an overestimation of recurrence
29 intervals. Based on these findings, we recommend giving priority to the scar-counting approach on small
30 diameter (<15cm) broadleaved stems and to restrict tree-ring analysis to old conifers that are more susceptible
31 – through the identification of tangential rows of traumatic resin ducts – to provide reliable estimations of long
32 recurrence intervals (as generally observed in the lower portions of the slope). These guidelines should help to
33 improve the reliability of recurrence interval maps of rockfall process activity in forests further, but also to
34 improve cost-benefit ratios of future studies.

35 **1. Introduction**

36 Rockfalls are widespread natural hazards in mountain regions where they threaten inhabited areas and transport
37 corridors, causing each year significant economic and human losses (Volkwein et al., 2011). They are commonly
38 defined as the detachment of a rock fragment from a steep rock wall (Selby, 1993) which then travels some
39 distance down the slope by bouncing, falling or rolling (Varnes, 1978). In general, fragmental rockfalls involve
40 relatively small detachments of isolated rocks or/and boulders with maximum volumes normally remaining <30
41 m³ (Dorren et al., 2007). Despite their limited volumes, rockfalls pose a significant hazard, due to their rapid
42 evolution, high velocity and impact energy, but their unpredictable occurrence hinders detailed investigation of
43 their dynamics and drivers under natural conditions. Typical approaches to deliver information about rockfalls
44 include (i) deterministic and probabilistic susceptibility analysis (Dietze et al., 2017), (ii) predictive modelling of
45 their potential propagation (Dorren et al., 2003), (iii) *a posteriori* mapping of detachment zones, released
46 volumes and trajectories by aerial and satellite imagery, repeat terrestrial laser scan (TLS), rockfall collector
47 surveying (Sass et al., 2005; Abellán et al., 2010) or seismic cliff monitoring (Dietze et al., 2017) as well as (iv)
48 rockfall inventories (Hungri et al., 1999; Dussauge, 2003). However, major efforts are still required to quantify
49 rockfall activity in terms of frequency and magnitude at the local scale, which is crucial for risk assessment, the
50 choice of appropriate mitigation measures, and for the validation of output from simulation runs.

51 On forested slopes, trees are reliable bio-indicators of past rockfall activity (Stoffel and Corona, 2014).
52 Dendrogeomorphology – an approach based on the analysis of damage inflicted to trees after rockfall impacts –
53 can be used to overcome certain gaps and limitations inherent to historical archives (Ibsen and Brunsden, 1995;
54 Sass and Oberlechner, 2012). Indeed, tree-ring reconstructions have been used in the past to (i) compute the

55 frequency of past events (Stoffel, 2006; Trappmann et al., 2014), (ii) map preferential trajectories of rockfalls,
56 (iii) identify climatic drivers of rockfall activity (Schneuwly and Stoffel, 2008a; Šilhán et al., 2011) as well as to (iv)
57 compare observed and/or reconstructed rockfall inventories with process activity as predicted by three-
58 dimensional, process-based rockfall models (Stoffel et al., 2006; Corona et al., 2013; Corona et al., 2017. Table 1
59 provides a synthesis of rockfall research realized with tree rings). The main weakness of these
60 dendrogeomorphic approaches is the substantial time effort required for exhaustive sampling (with cross-
61 sections and cores), identification, cross-dating, and dating of growth disturbances forming after mechanical
62 disturbance by rockfall impacts. Trappmann and Stoffel (2013, 2015) and Favillier et al. (2017) have suggested
63 the counting of visible scars as an alternative method requiring much less time and efforts as compared to
64 conventional dendrogeomorphic approaches when it comes to the reconstruction of spatial patterns of rockfall
65 activity. Yet, to date, the two approaches have not been compared systematically at a single site and for a
66 common dataset.

67 In this context, based on a procedure that includes (i) an extraction of a representative number of trees from an
68 exhaustive forest inventory, (ii) the estimation of tree ages from allometric curves and increment cores as well
69 as (iii) the quantification of rockfall-related growth disturbances based on the visual inspection of stems and
70 tree-ring analyses, this paper aims at comparing recurrence interval maps derived from both approaches so as to
71 evaluate their respective reliability as well as their advantages and inconveniences. To quantify potential biases
72 related to tree species in rockfall frequency estimation, as previously evidenced by Trappmann and Stoffel
73 (2013) and Favillier et al. (2017), our study was conducted in a mid-altitude (1500 m asl) mixed forest stand from
74 the Vercors massif (French Alps).

75 **2. Study site**

76 The study site is located in the municipality of Saint-Guillaume (256 inhabitants) on the northern slope of the
77 Pale mountain, at a locality named "Rocher du Bouchet" (44°56'18"N, 5°35'11"E, 1350 - 1490 m asl, Fig. 1a). At
78 this site, rockfall is frequent and fragments are normally detached from several release zones of a roughly 90-m-
79 high north-east-facing cliff (1450-1540 m asl, Fig. 1b). Bedrock in the release areas is composed of
80 subhorizontally bedded Jurassic limestone (Tithonian) with narrow orthogonal joints which favor the release of
81 small rock fragments with volumes ranging from a few dm³ to a few m³ (Fig. 1e). In the adjacent transit area

82 (1380–1490 m asl) Quaternary deposits are mainly composed of a scree talus covered by a mixed forest stand.
83 This scree slope is characterized by a marked longitudinal sorting of debris with volumes of a few dm³ at the
84 apex to a few m³ in the lower portion. The angle of the talus slope varies between 26° and 46° (average: 38°).
85 The bottom of the slope, located at an altitude of ~ 1100 m, is limited by a topographic berm (10°).
86 The tree plot area analyzed here (Fig. 1c) is located at the foot of the cliff. The plot is about 1 ha (110 × 90 m) in
87 size and is covered by a dense (800 trees ha⁻¹) mixed forest stand mainly composed of *Abies alba* (Silver fir),
88 *Picea abies* (Norway spruce), *Acer pseudoplatanus* (Sycamore maple), *Fagus sylvatica* (Common beech), *Fraxinus*
89 *excelsior* (European ash), *Sorbus aria* (White beam), *Sorbus aucuparia* (Mountain ash) and *Ulmus glabra* (Elm).
90 Evidence of past logging (stumps) is lacking at the study site, yet some silvicultural exploitation over the course of
91 the last century cannot be ruled out completely. Average annual rainfall (1961-2013) at the Grenoble
92 meteorological station (45°09'58"N, 5°45'58"E, 220 m asl), located 40 km North of the study site, is 934 mm.
93 Average mean air temperature is 12.5 ° C. Rockfall is the dominant geomorphic process on the slope and is
94 responsible for a vast majority of the scars observed on the tree stems. Other geomorphic processes cannot be
95 totally excluded, especially in the uppermost portions of the talus slope, where snow avalanches of limited
96 extent are susceptible to occur. No data on past geomorphic events exist in municipal records.

97 **3. Material and methods**

98 *3.1. Preliminary step: systematic tree plot*

99 In a first step, a full tree positioning and mapping procedure was used so as to build a database for the
100 assessment of rockfall activity at the site. Trees with a diameter at breast height (DBH) > 5 cm were
101 systematically located in the 110 × 120 m tree plot orientated perpendicular to the line of maximum slope
102 gradient (Fig. 1c, 2a). The position of each tree was determined with decimetric precision using a sonic
103 rangefinder, compass, and inclinometer. Information on tree species and diameter was recorded in a database.
104 In total, 793 trees were positioned in a geographical information system (GIS) as geo-objects. This systematic
105 tree plot was then used as a basis for a stratified random sampling strategy. To this end, the initial tree
106 population was divided into five sub-groups (DBH<15 cm, 15-25cm, 25-40cm, 40-60cm, >60cm), on the basis of
107 tree species and diameter. The size of each subgroup, fixed so as to be representative of the diameter spectrum
108 observed at the stand scale, thereby varied between n=19 for DBH>60cm and n=39 for DBH=15-25cm. Each

109 randomly selected stem was visually inspected and cored with an increment borer with the final aim of
110 comparing the scar counting and the dendrogeomorphic approaches.

111 *3.2. The visual scar-counting approach*

112 Trappmann and Stoffel (2013, 2015) and Favillier et al. (2017) have previously demonstrated the reliability of the
113 visual scar-counting approach to reconstruct spatial patterns of rockfall activity. For each tree extracted from the
114 random sampling, recent scars were thus identified according to their appearance, chipped bark, or injured
115 wood, following the approach described by Trappmann and Stoffel (2015). Wounds that were about to overgrow
116 at the time of sampling were identified by the callus pad sealing the injuries from the margin toward the center
117 (Stoffel and Perret, 2006, Fig. 1d). Older, completely healed injuries were more difficult to be detected visually,
118 especially in tree species with thick barks (Stoffel and Perret, 2006); they were inferred via the occurrence of
119 “swellings” and blisters on the stem surface. Extremely long, vertical scars or scars with vertical extensions < 3
120 cm were excluded to avoid misclassification and/or the inclusion of injuries caused by branch breakage or falling
121 neighboring trees (Perret et al., 2006).

122 *3.3. Development of age–diameter regression models*

123 In a second step, logarithmic diameter-age regression models (Rozas, 2003) were built for the conifer (*P. abies*,
124 *A. alba*) and broadleaved (*A. pseudoplatanus*, *F. sylvatica*, *F. excelsior*, *S. aria*, *S. aucuparia*, *U. glabra*) tree
125 species at the stand scale. To this end, a total of 109 undisturbed trees with a DBH \geq 10 cm were cored using a
126 Pressler increment borer. Trees were selected according to five diameter classes, representative at the tree plot
127 scale. Samples were analyzed and data processed following standard dendrochronological procedures (Bräker,
128 2002). In the laboratory, tree rings were counted using a digital LINTAB positioning table connected to a Leica
129 stereomicroscope. Missing rings toward the pith were estimated from ring curvature (Villalba and Veblen, 1997;
130 Bollschweiler et al., 2008). In a final step, we used data from the logarithmic regression models to estimate tree
131 ages of individual trees selected from random sampling for which scars were identified and counted on the stem
132 surface and for which the DBH has been measured.

133 *3.4. Dendrogeomorphic analyses*

134 As our study aims at comparing the recurrence intervals of rockfalls derived from the scar-counting approach
135 and from classical dendrogeomorphic analysis, event histories at the level of individual trees were reconstructed
136 as well through the analysis of tree-ring sequences. For each tree extracted from the random sampling, an
137 increment core (max. 40×0.5 cm) was taken at the lateral edges of each visible scar (i.e. at the contact of the
138 unaffected wood with the overgrowing callus tissue; Sachs 1991, Larson 1994; Schneuwly and Stoffel, 2008b).
139 For this investigation, the first layer of callus tissue within the tree-ring was used to determine the timing of
140 rockfall activity. For conifers, known to mask injuries efficiently, tangential rows of traumatic resin ducts (TRDs;
141 Bannan, 1936; Stoffel and Bollschweiler, 2008) formed next to and at some distance of the impact scar
142 (Schneuwly et al., 2009a, 2009b) were used as a further indicator to date past rockfalls (Stoffel, 2006). Resin
143 ducts were only considered the result of rockfall activity if they formed traumatic, compact, continuous and
144 tangential rows (Stoffel et al., 2005a). In addition, based on the distribution of observed scars (which remain
145 usually below 2m at the study site), one increment core was systematically extracted, in the fall line, at 0.5, 1.0,
146 and 1.5 m, in order to increase the likelihood to retrieve old, completely healed impacts. The 0.5 m core was also
147 used to estimate the cambial age of each tree.

148 Following Stoffel et al. (2005 a, b), (i) abrupt suppression of tree growth indicating decapitation or branch loss,
149 (ii) presence of callus tissue and TRD next to (blurred) injuries; (iii) eccentric growth and the formation of
150 reaction wood following stem tilting; and (iv) abrupt growth release (suggesting that neighboring trees were
151 eliminated and the surviving trees benefited from improved growth conditions such as enhanced access to light,
152 water, and nutrients) were used as additional evidence of past rockfall impacts.

153 *3.5. Estimation of recurrence interval of individual rockfall impacts*

154 The assessment of recurrence interval is a classical concept that is regularly used in the analysis of all types of
155 hazards, but it was only introduced very lately into dendrogeomorphology to inform avalanche zoning (Corona
156 et al., 2010; Schläppy et al., 2013; Favillier et al., 2018) or rockfall risk assessments (Šilhán et al., 2013;
157 Trappmann et al., 2014, Favillier et al., 2015, 2017). In dendrogeomorphology, recurrence intervals represent
158 the average time passing between two successive impacts at a specific point (i.e., the surface of an individual
159 tree for which the position on the slope is known) as follows:

$$160 \quad RiV = \frac{AVt}{ScVt} \quad (1)$$

161
$$RiD = \frac{ADt}{ScD} \quad (2)$$

162 where RiV and RiD represent the recurrence intervals computed from the visual scar-counting and
 163 dendrogeomorphic approaches, respectively; AV_t and AD_t indicate the age of each tree as derived from the
 164 dendrometric assessment and tree-ring counting, respectively; and ScV_t and ScD_t show the number of scars
 165 that were visually observed on each stem t and retrieved from tree-ring analysis, respectively.

166 The study area was clustered into $\sim 55 \text{ m} \times 30 \text{ m}$ cells for further analysis (Fig. 1c). Mapped trees were then
 167 assigned to cells according to their location. The distributions of tree ages, growth disturbances, and recurrence
 168 intervals were compared at the plot and cell scales. A systematic comparison was also realized between conifer
 169 and broadleaved trees. Due to their non-normal distributions, the non-parametric Wilcoxon-Mann-Whitney
 170 (WMW) test was used to compare tree ages, growth disturbances, and recurrence intervals for conifer and
 171 broadleaved trees at the plot and cell scales.

172 **4. Results**

173 *4.1. Recurrence intervals derived from the scar-counting approach*

174 The logarithmic diameter-age regression models for the conifer and broadleaved tree species at the tree plot are
 175 given by the following equations:

176
$$Age_{B_t} = 50.148 \ln(D_t) - 57.696 \quad (n = 43, r^2 = 0.61, p < 0.001) \quad (3)$$

177
$$Age_{C_t} = 49.545 \ln(D_t) - 62.907 \quad (n = 66, r^2 = 0.67, p < 0.001) \quad (4)$$

178 where Age_{B_t} and Age_{C_t} represent the estimated ages for each broadleaved and conifer tree (t), respectively;
 179 and where $\ln(D_t)$ represents the Neperian logarithm diameter of tree t .

180 According to these models, conifers grow faster than broadleaved trees. Conifer and broadleaved trees with
 181 radii of 20 cm are theoretically aged 93 and 85 years, respectively. The oldest conifer (*A. alba*) randomly
 182 extracted from the tree plot was 236 years old (DBH = 112 cm) whereas the oldest broadleaved tree (*F.*
 183 *sylvatica*) was only 176 years old (DBH = 176 cm). At our study plot, and according to the diameter-age
 184 regression models, the 278 trees randomly extracted from the tree plot averaged 90 ± 35 years (i.e. 87 ± 30
 185 years for 99 broadleaved trees and 91 ± 37 years for 179 conifers). The Wilcoxon-Mann-Whitney test revealed
 186 that the distributions by tree species are not statistically different.

187 On the basis of the scar-counting approach, 815 scars (475 on conifers, 340 on broadleaved trees) were
188 identified on the 278 stems that were randomly extracted and visually inspected. A total of 39 of the selected
189 trees (14%) did not present any visual evidence of past rockfall impacts. On average, 2.9 (\pm 2.4) injuries were
190 counted on tree stems, 3.4 (\pm 2.5) and 2.6 (\pm 2.3) on broadleaved and conifer trees, respectively. Noteworthy,
191 both distributions are statistically different ($p < 0.05$). From a spatial perspective, the scar-counting approach
192 clearly evidences the existence of a downslope gradient in scar numbers. The average number of injuries per
193 stem thus decreases from 4.4 on the top third of the plot (cell B) to 3.2 in the central part (cell D), and 1.9 on the
194 lower third (cell F). Cell E ($0.9 \text{ scar} \cdot \text{stem}^{-1}$) appears as the least active area within our study plot.

195 At the plot scale, recurrence intervals of rockfall were computed as the ratio between tree ages estimated from
196 regression models and the number of injuries observed on each tree stem. Based on the data used, the average
197 recurrence interval is 38 years. The distributions of RiV statistically differ ($p < 0.05$) between conifer (mean: 45
198 years) and broadleaved (mean: 31 years) trees. The recurrence interval map (Fig. 3a) exhibits an increasing trend
199 as one moves down the slope: the average time elapsed between two consecutive scars by the scar-counting
200 approach gradually increases from an average of 15-25 years in the top third of the slope (cells A–B) to reach
201 values of 50-150 years in the lowest third of the plot (cells E–F), at the level of the topographic berm. The map
202 also evidences a clear lateral zonation pattern with more frequent rockfalls observed in the northwestern part of
203 the plot ($RiV = 25$ and 51 years in cells B and D, respectively) as compared to its eastern counterpart ($RiV = 52$
204 and 67 years in cells A and C, respectively). Except for cell B ($p < 0.05$), recurrence intervals estimated from
205 broadleaved and conifers trees were not statistically different (Fig.4).

206 *4.2. Recurrence intervals derived from tree-ring analysis*

207 In total, 1097 increment cores have been sampled on the 278 impacted stems. On average, tree ages were
208 comparable for conifer (85 ± 42 years) and for broadleaved trees (84 ± 44 years) and their distributions did not
209 differ statistically. In total, dendrochronological analysis allowed identification of 810 rockfall events (207 on
210 broadleaved trees and 603 on conifers), mainly detected in the form of injuries (55%), tangential rows of
211 traumatic resin ducts (TRDs, 24%), and growth suppressions (16%) (Tab. 2). The mean number of growth
212 disturbances (GDs) per stem (2.9 ± 2.7 GD) was greater for conifers (3.4 ± 2.8 GD) than for broadleaved trees (2.1
213 ± 2 GD). Amongst the 810 reconstructed events, 243 (30%) were reconstructed from growth disturbances that
214 were not visible on the stem surface, mainly in the form of overgrown injuries (38%), TRDs (31%) and growth

215 suppressions (26%). The percentage of growth disturbances retrieved from increment cores but not visible on
216 the stem surface was significantly higher on conifers than on broadleaved trees (36 and 10%, respectively). The
217 ratio between visible and invisible growth disturbances (GD) exceeded 45% for conifers > 25 cm, but was only
218 10% for large-diameter broadleaved trees (Fig. 5).

219 At the plot scale, the recurrence interval is 32 years on average and the distributions of *RiD* statistically differ
220 ($p < 0.05$) between conifer (mean: 30 years) and broadleaved (46 years) trees. In spatial terms, the *RiD* increases
221 from 10-25 years in the upper third of the study plot to 50-150 years in its lower part. A lateral gradient is
222 superimposed on this longitudinal zonation: more frequent activity is thus observed in cells B, D, and F (*RiD* = 21,
223 45, and 65 years, respectively) than in cells A, C, and E (*RiD* = 49, 63, and 90 years, respectively) (Fig. 3b).
224 According to the Wilcoxon-Mann-Whitney test, distributions of recurrence intervals from broadleaved and
225 conifer trees are statistically different in cells D and E ($p < 0.05$) (Fig. 6).

226 4.3. Comparison of both approaches

227 To compare both approaches, we computed differences between tree ages, number of GDs and recurrence
228 intervals between the scar-counting and dendrogeomorphic analyses and at the scale of individual trees. With
229 respect to tree ages estimated from the (i) age-diameter relation and (ii) the dendrogeomorphic approach, the
230 mean difference between both approaches was 7 years. Noteworthy, however, the difference was in the range
231 ± 20 years in 50% of the trees (46% for conifers, 54% for broadleaved trees), and exceeded 50 years in 35 trees
232 (12.5%; 17 conifers and 18 broadleaved trees). Differences clearly increased with stem diameter (Figs. 3c,
233 3d,7a), yet, age distributions derived from logarithmic regressions and tree-ring analyses were not statistically
234 different.

235 In 25% of the trees ($n=69$), the number of injuries counted at the stem surface was equal to the number of
236 growth disturbances in the tree-ring series. The differences ranged between -2 and +2 scars for 78.5% of the
237 trees, and exceeded 5 scars on 15 trees (5%). In the case of the conifers, the number of growth disturbances
238 retrieved from tree-ring analysis was frequently greater than the number of injuries observed on the stem
239 surface (Fig. 7b). Conversely, in the case of broadleaved trees, the visual counting approach tended to
240 overestimate the number of injuries. According to Fig. 7b, these differences were not diameter-dependent.
241 From a spatial perspective, the number of scars observed on broadleaved stems exceeded the number of GDs

242 detected in the tree-ring series significantly ($p < 0.05$) in cells B, D, and E. In the case of conifers, differences
243 between both approaches were significant in the lower third of the plot in cells E and F.

244 In 42.5% ($n = 119$) of all trees, differences between the scar counting and the dendrogeomorphic analyses were
245 less than 10 years in terms of recurrence intervals. In 14% of the stems, values, however, exceeded 50 years.
246 According to the Wilcoxon-Mann-Whitney test, RiV and RiD distributions (fig. 7c) did not differ statistically,
247 neither at the plot nor at the cell scales. Paradoxically, differences between the mean recurrence interval
248 computed from the visual and dendrogeomorphic series were statistically significant at the 5% level if conifer
249 and broadleaved trees were considered separately at the plot scale. Unsurprisingly, the recurrence interval maps
250 showed comparable downslope gradients and confirmed the difference between the northwestern and
251 southeastern compartments of the plot analyzed in this study. At the cell scale, recurrence intervals derived
252 from both approaches differed ($p < 0.05$) for broadleaved trees in the northwestern (cells B and D) and for
253 conifers in the lower (cells E and F) compartments of the plot.

254 **5. Discussion**

255 *5.1. Convergence between the scar-counting and the dendrogeomorphic approaches*

256 Long-term records of rapid mass movements, such as rockfalls, have proven to be limited. This lack of
257 inventories is especially detrimental in urbanized areas (Dorren et al., 2007; Volkwein et al., 2011) where risk is
258 often increasing disproportionately with ongoing urbanization (Baillifard et al., 2004). In these areas, finding ways
259 that allow precise reconstruction of past rockfall activity are urgently needed. In case that such slopes are
260 forested, growth disturbances in trees are a reliable option that allows one to reconstruct past rockfall activity in
261 the absence of any inventory or clear morphological evidence, such as scree slopes or isolated blocks (Volkwein
262 et al., 2011) by , either inspecting stems visually (Trappmann and Stoffel, 2013; Favillier et al., 2015, 2017;
263 Eichenberger et al., 2017) or by analyzing the tree-ring records of impacted trees (Alestalo, 1971; Stoffel et al.,
264 2010). Based on a stratified, random sampling of 278 trees from an exhaustive mapping of 1004 trees in a mixed
265 forest stand, we compared, for the first time, recurrence intervals derived from both approaches in a 1-ha plot.
266 The systematic counting of visible scars yielded 810 records on all tree stems and the dendrogeomorphic
267 approach allowed identification of 815 growth disturbances in tree-ring series.

268 This comparison represents a significant improvement with respect to former studies. Indeed, whereas Favillier
269 et al. (2015) showed that significant differences exist in recurrence intervals between *Acer opalus* and *Quercus*
270 *pubescens* based on scar counting, they did not compare their result with tree-ring analyses. Trappmann and
271 Stoffel (2013) compared both approaches but used tree-ring analysis from a conifer species (*Picea abies*) and
272 visual scar counting on broadleaved trees (*F. sylvatica*). They concluded that the absolute numbers of rockfalls
273 (and hence return intervals) vary significantly between the approaches, and that the mean number of rockfalls
274 observed on the stem surface of *F. sylvatica* exceeds that of *P. abies* by a factor of ~ 3 . On the other hand, both
275 methods yielded comparable data on the spatial distribution of relative rockfall activity.

276 Based on the results of this study, Fig 8 synthesizes the recurrence intervals obtained from both approaches, at
277 the plot (Fig. 8a) and cell (Fig. 8 b-g) scales, and for conifer and broadleaved species. At the plot scale, mean
278 recurrence intervals (38 and 32 years) computed from both approaches are comparable. The marked downslope
279 decrease in the number of observed scars per stem is consistent with the well-known frequency reduction of
280 fallen blocks down the slope (Gsteiger, 1989; Dorren et al., 2005, 2006, 2007). In addition, both approaches
281 converge to show a clear difference between the northwestern (more active) and eastern (less active)
282 compartments of the plot. This convergence is confirmed regardless of the cell considered, and the Wilcoxon-
283 Mann-Whitney test does not point to any significant difference in mean recurrence intervals between the scar-
284 counting and dendrogeomorphic methods. These results suggest that the visual scar counting (Trappmann and
285 Stoffel, 2013; Favillier et al., 2017) represents an efficient and effective alternative to the time-consuming
286 dendrogeomorphic approach when it comes to the spatial assessment of rockfall activity on larger surfaces, as it
287 can be realized with limited temporal and financial efforts.

288 5.2. Differences between conifers and broadleaved trees

289 Despite the overall convergence of both approaches based on the full dataset of trees, one should keep in mind
290 that rockfall recurrence intervals differ strongly as soon as conifer or broadleaved trees are considered
291 separately. At the plot scale, these differences in return periods computed from both approaches amount to +14
292 years and -16 years for broadleaved and conifer trees, respectively (Fig. 8). In other words, the number of
293 injuries counted on conifer stems is lower than the number of growth disturbances retrieved from the
294 dendrogeomorphic approach. By contrast, in the case of broadleaved trees, the visual inspection tends to
295 overestimate the frequency of past rockfall activity. The fact that comparable mean recurrence intervals are

296 obtained from the full dataset therefore results from a compensatory effect, meaning that higher recurrence
297 intervals computed from the visual inspection of broadleaved trees are counterbalanced by lower intervals
298 derived from conifer trees. Similarly, the more frequent growth disturbances identified in the tree-ring series of
299 conifers compensate for the reduced number of injuries retrieved from the tree-ring series of broadleaved trees.
300 The main reason for such interspecific differences are the hidden scars. The masking of wounds can be highly
301 variable as a result of the initial size of the injury, vitality of the tree, its genetic capability to overgrow injuries,
302 bark structure, annual increment rates, or tree age, just to name a few reasons. Yet, in general, tree species with
303 a thick and structured bark will mask scars more efficiently than those with thin and smooth bark structures
304 (Stoffel and Perret, 2006; Trappman and Stoffel, 2013; Favillier et al., 2015). Stoffel (2005), for instance, could
305 identify 75% of all scars by visual interpretation of bark structures on *F. sylvatica*, whereas only 51% of the
306 injuries remained visible on the stem surface of *P. abies*.

307 At our study site, we can reliably assume that thick-barked conifer trees mask scars of past events very
308 efficiently. As a consequence, old scars are difficult to detect, unless wound callus pads remain clearly visible on
309 the stem surface (Larson, 1994; Fink, 1999). One could argue that the rapid healing could also render the
310 determination of suitable coring positions a difficult task and that older events could be missed on increment
311 cores as well. Yet, the dominant conifer species, *A. alba*, *P. abies*, both react to mechanical damage with the
312 formation of tangential rows of traumatic resin ducts (Lepage and Bégin 1996; Stoffel and Perret 2006;
313 Bollschweiler et al. 2008) with a tangential spread on more than one-third of the circumference (Schneuwly and
314 Stoffel, 2008b). These TRDs that represent one-fourth of the GD dated in the tree-ring series therefore make it
315 possible to overcome the difficulty related to masked scars.

316 By contrast, broadleaved species generally have a thinner and smoother bark structure which not only facilitates
317 wounding but also enhances longer-term visibility of scars on the stem surface (Stoffel, 2005; Stoffel and Perret,
318 2006). Based on micro-section analyses, Arbella et al. (2010, 2012) demonstrated that injured rings of *Betula*
319 *pendula* and *Fraxinus excelsior* were characterized by smaller vessels. Yet, these anatomical changes were only
320 visible in a 30° radial segment around the injury. Arbella et al. (2012) thus recommended taking samples, ideally
321 wedges or cross-sections, closer to the injury in the case of diffuse-porous species so as to increase the potential
322 detection of past events. At our study site, the greater persistence of past injuries on thin-barked broadleaved
323 species and the complexity to detect hidden scars from increment cores probably explain the discrepancies
324 between the scar-counting and dendrogeomorphic approaches.

325 Interestingly, at the plot scale and in cells A-D, the recurrence intervals computed from the visual inspection of
326 broadleaved stems are comparable to those derived from the analysis of increment cores for conifers (Fig. 8). In
327 the upper part of our plot, characterized by small diameter trees, this similarity allows us to partly rule out the
328 hypothesis formulated by Trappmann and Stoffel (2012) and Favillier et al. (2015) that thick bark constitutes a
329 mechanical barrier that is able to buffer low energy rockfalls and thus damage to the underlying tissues. In other
330 words, we cannot consider at the Saint-Guillaume site that the bark of young conifers is sufficiently thick to
331 protect the underlying cambium from mechanical abrasion caused by rockfall events. Similarly, the scar counting
332 approach does not seem to overestimate rockfall activity by single rocks leaving multiple scars or by rock
333 fragmentation causing a higher number but smaller volume of blocks, leaving multiple impacts (Trappmann and
334 Stoffel 2013; Trappmann et al., 2014).

335 *5.3. Recommendations for hazard zoning*

336 Based on the findings of this study and with the aim of improving cost-benefits ratios in rockfall hazard zoning in
337 mixed forest stands, we recommend future works to:

- 338 (1) give priority to the scar-counting approach on small diameter (<15cm) broadleaved stems in the upper
339 part of the slope, i.e. at the vicinity of cliff. Here, trees were demonstrated to yield similar rockfall
340 frequencies to those computed for coniferous trees, but with the much more time-consuming
341 dendrogeomorphic approach;
- 342 (2) restrict tree-ring analysis to old conifers, as they are more likely to provide reliable estimates of long
343 recurrence intervals through the identification of tangential rows of traumatic resin ducts. These older
344 conifers are generally located at the lower part of the slope;
- 345 (3) exclude, as far as possible, large-diameter broadleaved species from tree-ring analysis due to the
346 remaining complexity of detecting overgrown injuries in tree-ring records. Despite the stringency of our
347 sampling procedure – based on three additional cores taken systematically in the fall line direction at
348 0.5, 1.0, and 1.5 m – the detection of masked scars indeed represented less than 10% of all GDs found
349 in these trees;
- 350 (4) avoid the visual scar counting approach on large-diameter (> 25 cm) conifer trees as their thick bark
351 overgrows rapidly and efficiently past injuries, therefore leading to strong overestimations of
352 recurrence intervals.

353 **6. Conclusions**

354 On forested slopes, the frequency of recent rockfalls can be determined either through (i) the analysis of rockfall
355 injuries remaining visible on the tree surface or (ii) the dating of characteristic growth disturbances (such as
356 growth suppression, tangential rows of traumatic resin ducts or reaction wood) in tree-ring series. In this paper,
357 based on the analysis of 278 broadleaved and conifer trees, we demonstrate that both methods provide similar
358 results on spatial patterns, with an increase of rockfall recurrence intervals down the talus slope and a clear
359 lateral zonation of activity. Paradoxically, and despite the absence of significant differences between recurrence
360 intervals computed between the methods, our results also reveal that rockfall frequency differs quite
361 substantially with tree species and diameter: the visual inspection of conifer stems and the analysis of tree-ring
362 signals in large-diameter broadleaved trees typically leads to an overestimation of recurrence intervals. Based on
363 these results, we recommend to give priority to the scar-counting approach on small diameter broadleaved,
364 frequently impacted stems located in the upper part of the slopes and to restrict the conventional
365 dendrogeomorphic approach to large conifer stems. These recommendations on more suitable practices on how
366 to analyze forest stands in the future according to the tree species and diameter will not only help increase the
367 reliability of recurrence interval maps derived from the analysis of tree growth disturbances, but also improve
368 cost-benefit ratios, thus rendering the approach more attractive for practitioners and natural hazard authorities.

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502 2011

503 **Captions**

504 **Fig. 1.** The Saint-Guillaume study site (a) is located in the Vercors massif (French Alp), 40km south-west of
505 Grenoble. Rock fragments are detached from several release zones within a roughly 90-m-high, north east-facing
506 cliff (1450-1540 m asl, b). At the study plot (110 × 120m) – delimited by a red polygon (b) – all trees with
507 DBH>5cm were mapped (c) and injuries resulting from past rockfalls inventoried (d, e)

508 **Tab. 1.** Synthesis of rockfall reconstructions based on classical tree-ring analysis and the visual scar counting
509 approach.

510 **Fig. 2.** Spatial distribution and diameters at breast height (DBH; in cm) of trees at the study plot (a) and
511 representative stems that were randomly extracted for the comparison between the visual scar counting and
512 the dendrogeomorphic (tree-ring) approaches (b).

513 **Fig. 3.** Recurrence interval maps derived from the visual scar counting (a) and the dendrogeomorphic
514 approaches (b). Comparison between recurrence intervals derived from both approaches for (c) coniferous and
515 (d) broadleaved trees.

516 **Fig. 4.** Distribution of recurrence interval derived from the visual scar counting approach at the level of cells A-F.

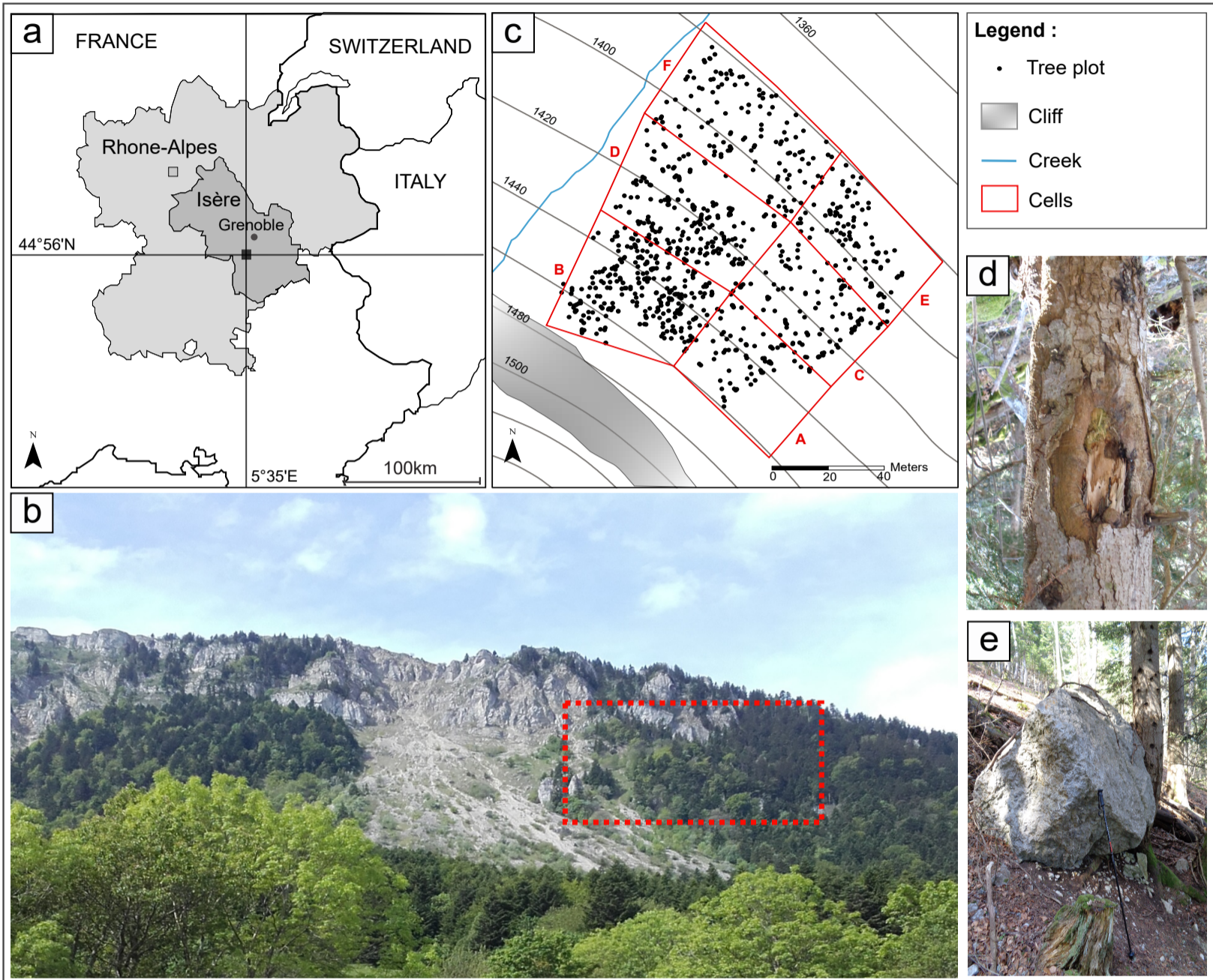
517 **Fig. 5.** Radar chart showing the distributions of the ratio between the numbers of visible / non-visible GD for four
518 stem diameter classes.

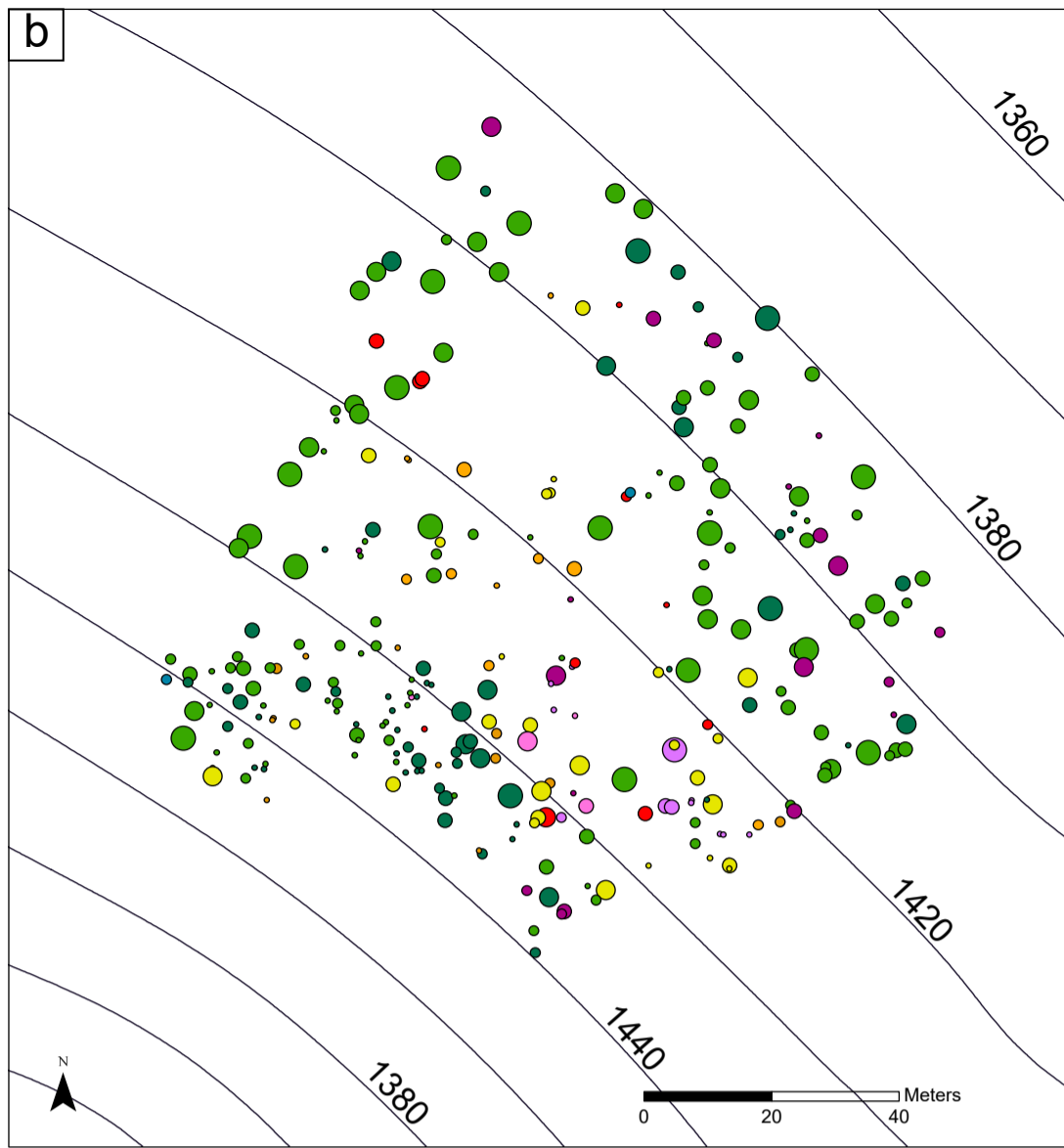
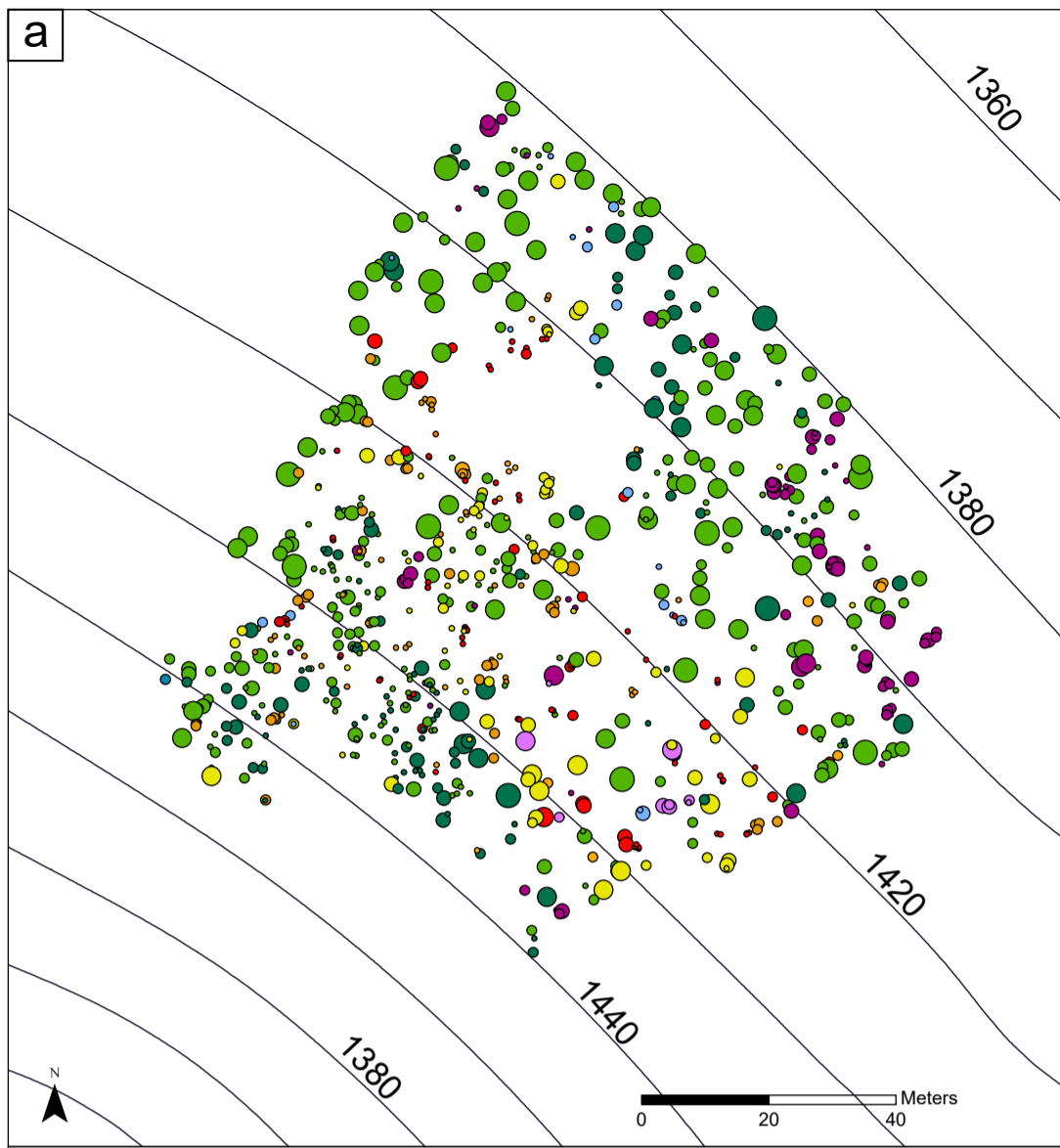
519 **Fig. 6.** Distribution of recurrence interval derived from the dendrogeomorphic approach at the level of cells A -F.

520 **Tab. 2.** Overview of growth disturbances (GD) identified in tree-ring series. TRD = tangential rows of traumatic
521 resin ducts.

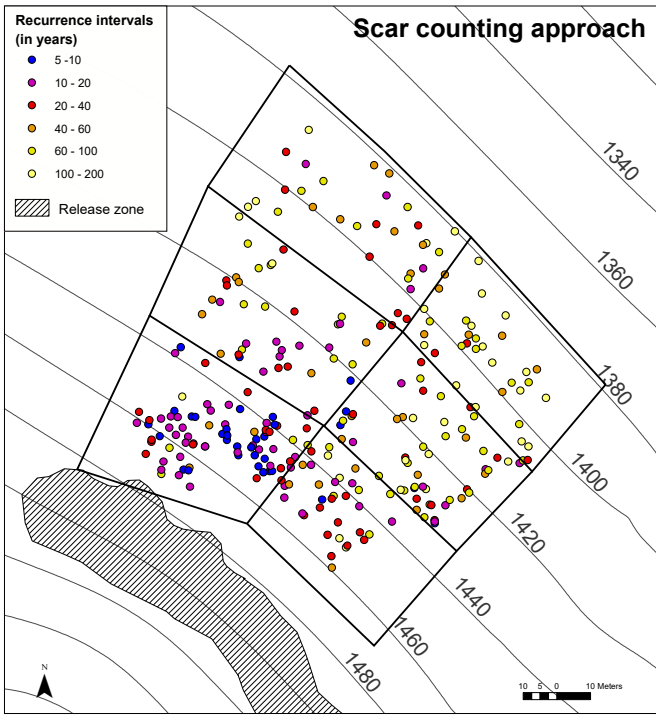
522 **Fig 7.** Distributions of differences between tree age (a), number of growth disturbances (b) and recurrence
523 intervals (c) between the visual scar counting and dendrogeomorphic approaches.

524 **Fig. 8.** Boxplots of recurrence intervals derived from the dendrogeomorphic and visual scar counting approaches
525 at the plot (a) and cell (b-f) scales. Blue and green tone colors are used for broadleaved and conifer trees,
526 respectively.

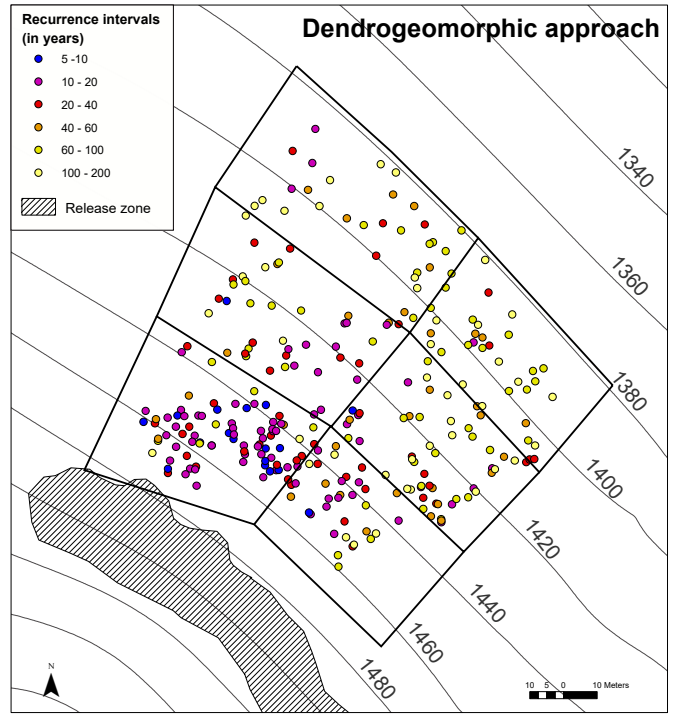




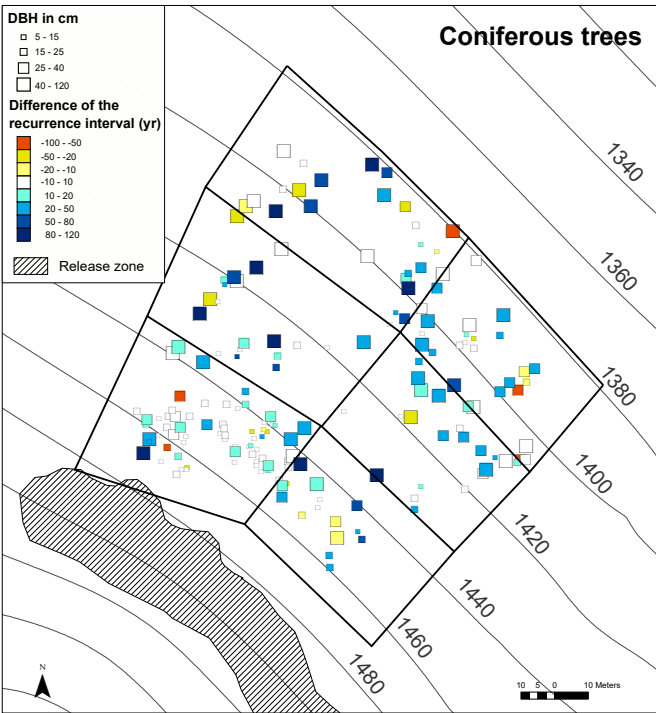
(a)



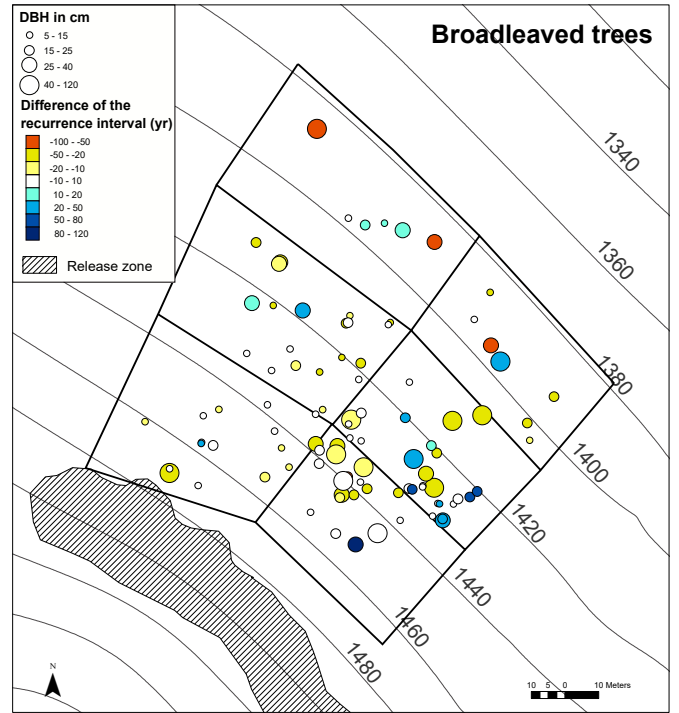
(b)

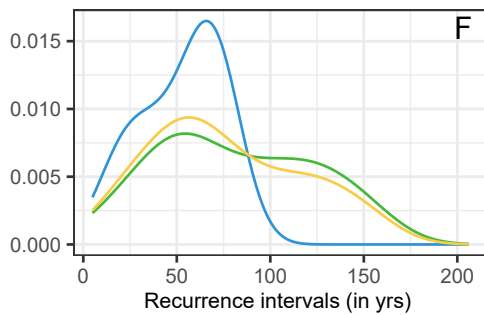
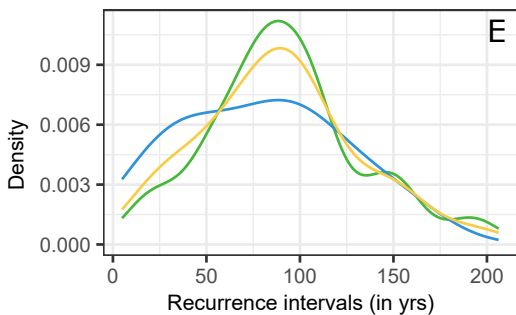
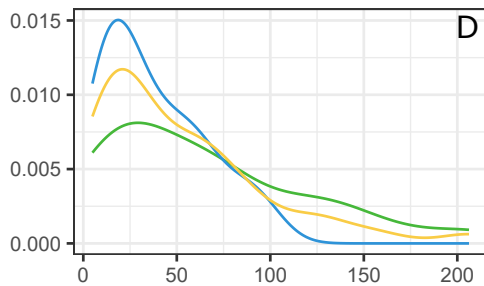
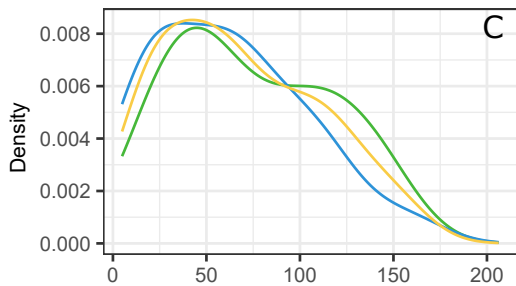
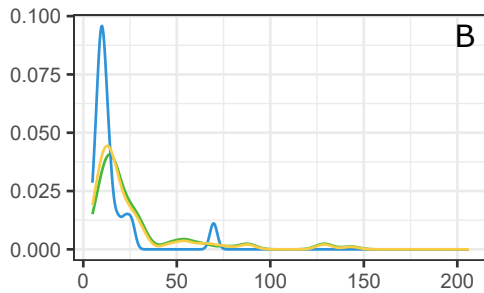
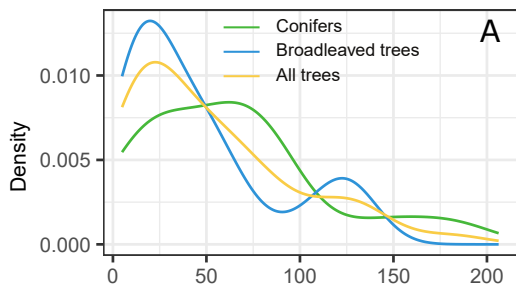


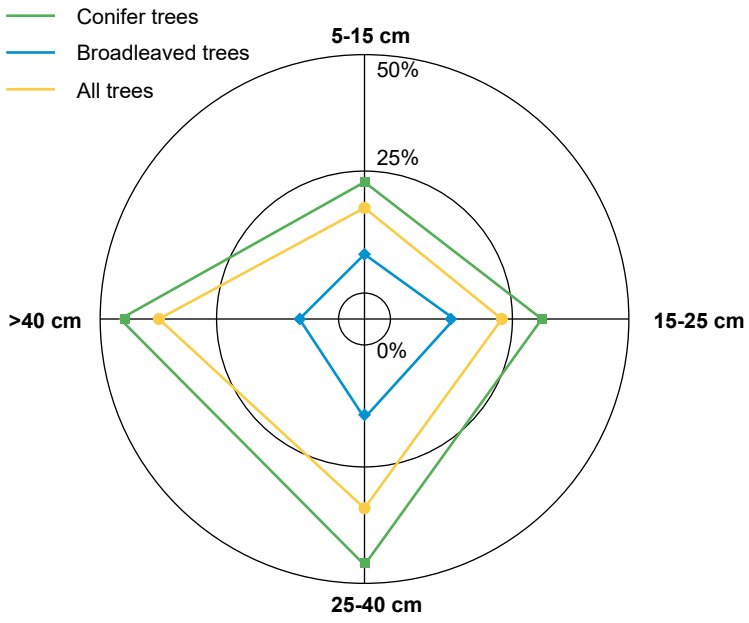
(c)

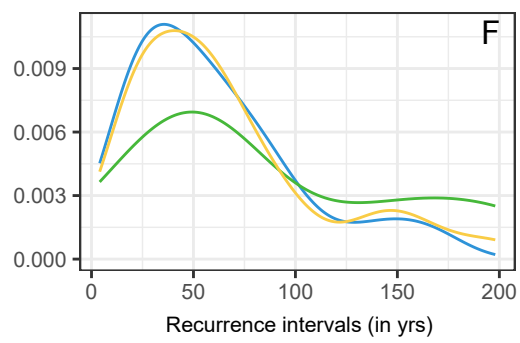
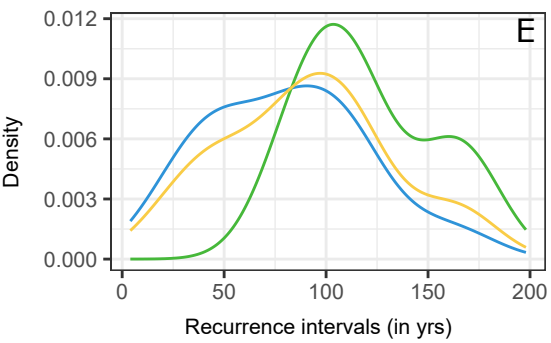
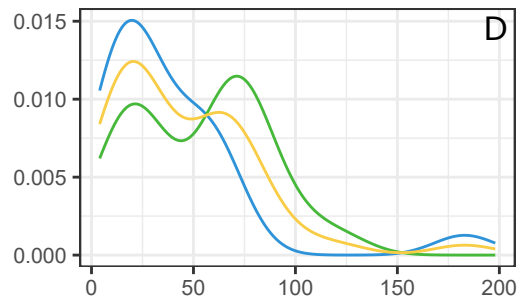
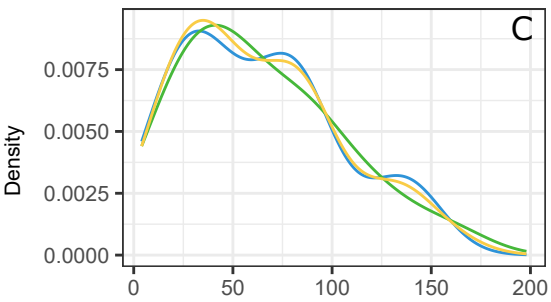
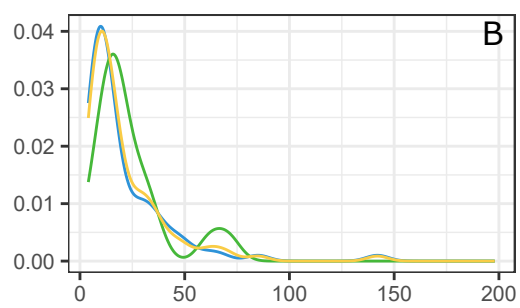
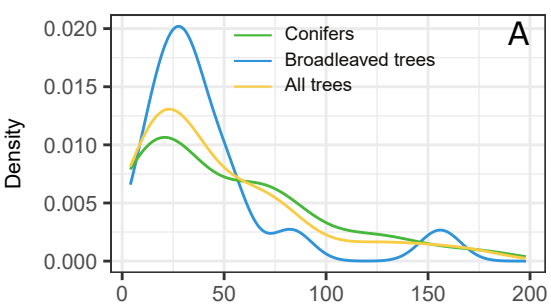


(d)

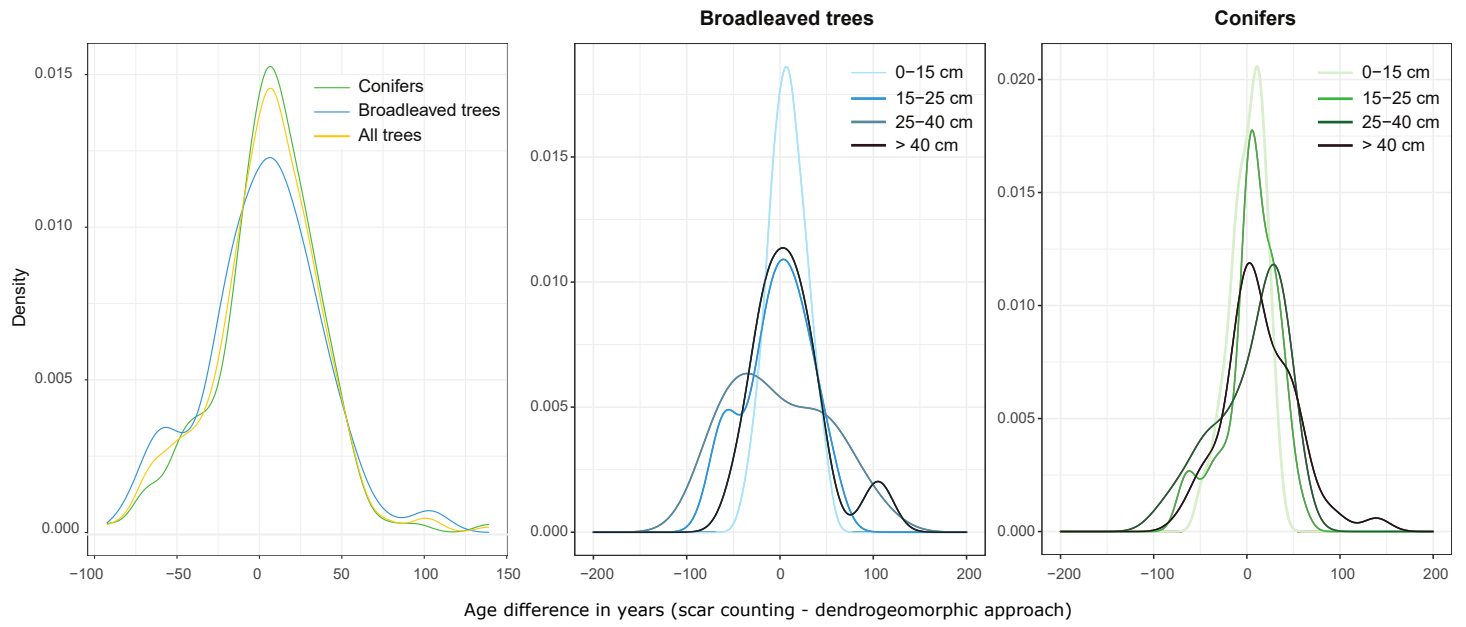




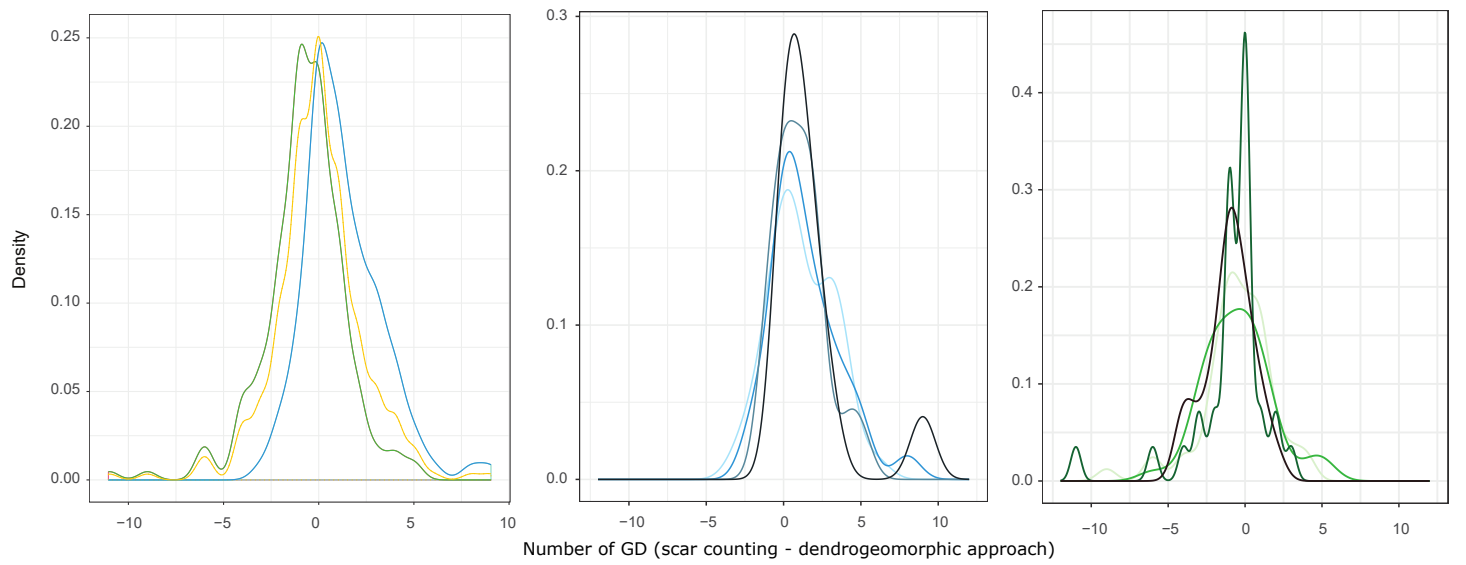




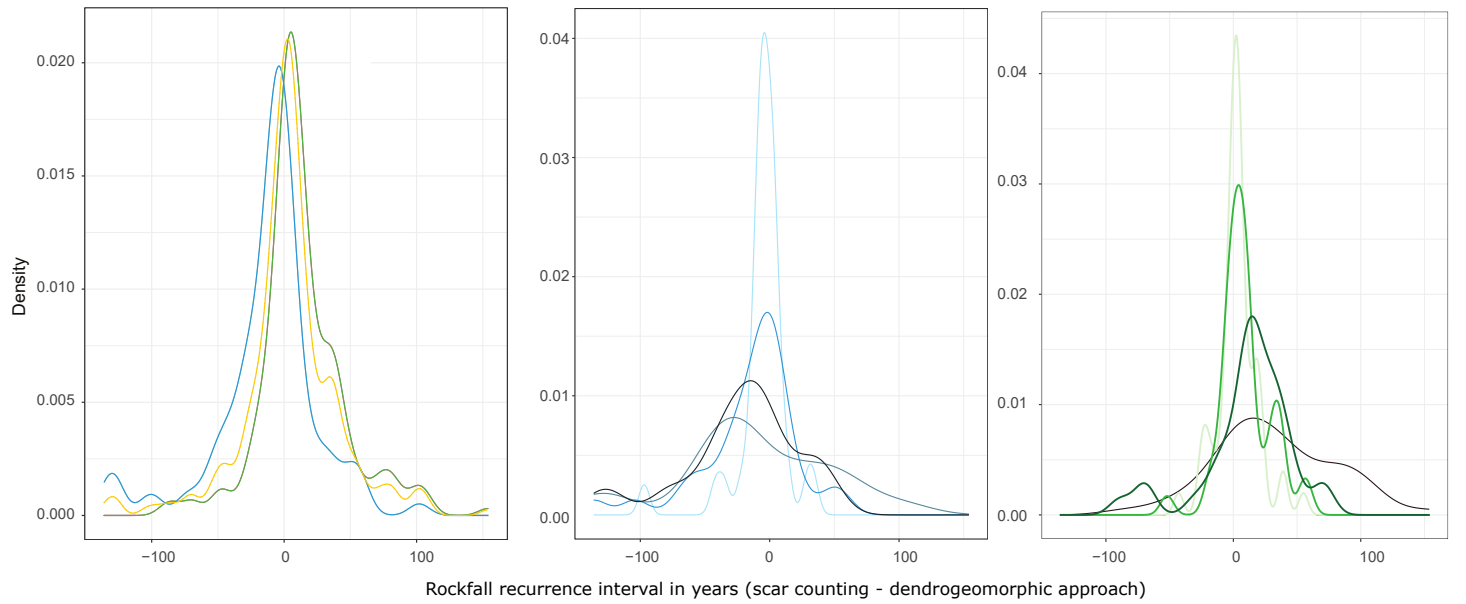
(a)

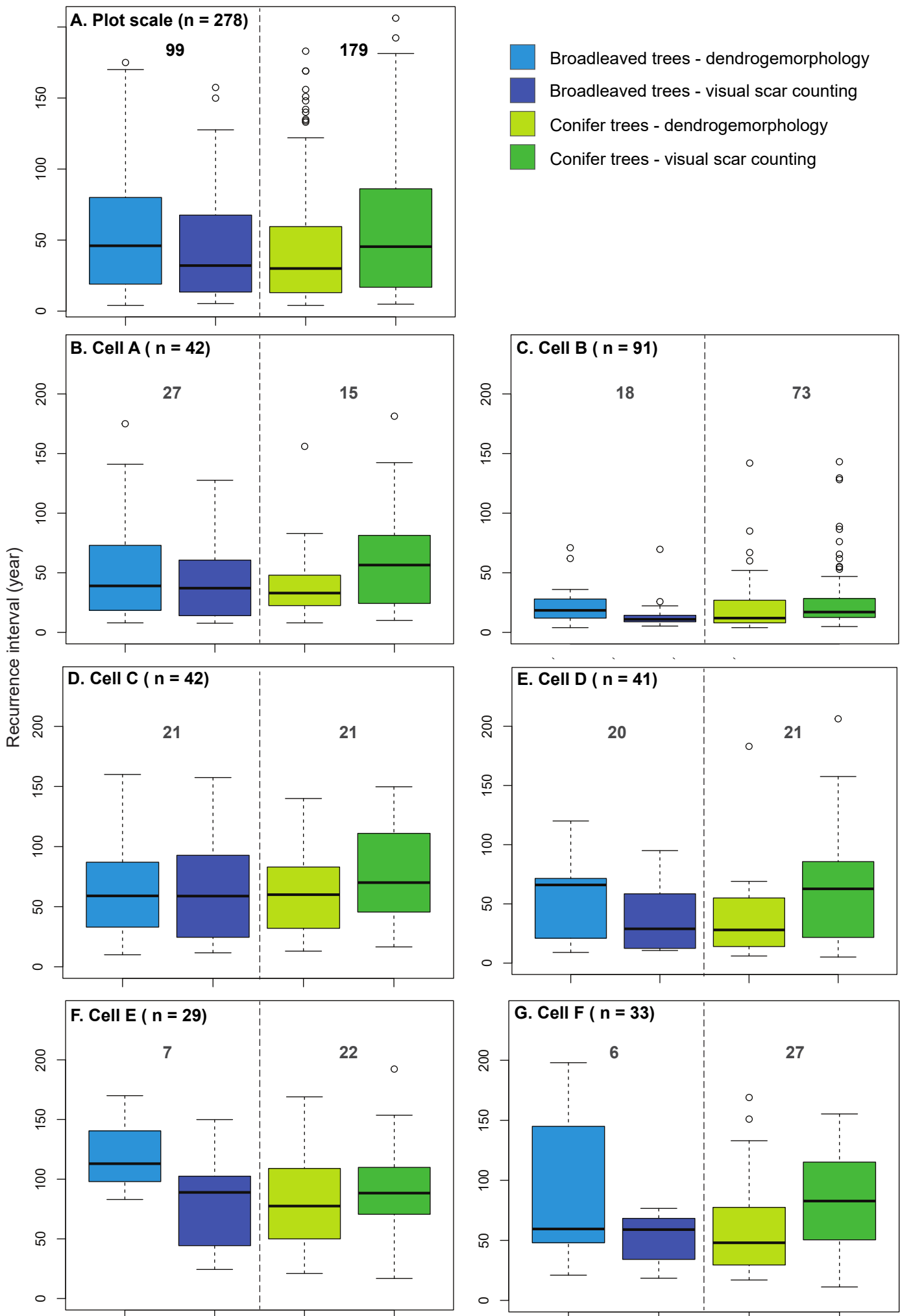


(b)



(c)





Authors	Year	Country	Species	Trees sampled	Number of samples	Number of events	Period	Altitude (m)	Sampling strategy	Representation of spatial activity
Gsteiger	1989, 1993	Switzerland	<i>P. abies</i> , <i>F. sylvatica</i>	7	25	56	unknown	\	stem discs	\
Schweingruber	1996	Switzerland	<i>P. abies</i>	30	30	66	1890-1987	\	stem discs	\
Stoffel et al.	2005a	Switzerland	<i>L. decidua</i>	18	270	180	1977-2001	2500	stem discs	\
Stoffel et al.	2005b	Switzerland	<i>L. decidua</i>	135	564	741	1740-2002	1600	increment cores	Recurrence interval
Perret et al.	2006	Switzerland	<i>P. abies</i>	33	33	250	1881-2000	1250	stem discs	Injuries/m ²
Schneuwly and Stoffel	2008a	Switzerland	<i>L. decidua</i> , <i>P. abies</i> , <i>Pinus cembra</i>	191	937	745	1957-2006	1600	increment cores, stem discs	Injuries m-1 year-1
Schneuwly and Stoffel	2008b	Switzerland	<i>L. decidua</i> , <i>P. abies</i> , <i>Pinus cembra</i>	32	123	149	1985-2006	1600	stem discs	\
Migoń et al.	2010	Poland	<i>P. abies</i>	32	62	unknown	1877-2007	900	increment cores, stem discs	\
Moya et al.	2010	Andorra	<i>Quercus robur</i> , <i>Quercus ilex</i>	276	375	73	1979-2002	2300	wedges, stem discs	\
Šilhán et al.	2011	Czech Republic	<i>Acer pseudoplatanus</i> , <i>F. sylvatica</i> , <i>P. abies</i> , <i>Sorbus aucuparia</i> , <i>Ulmus glabra</i>	283	1132	989	1931-2008	\	increment cores	\
Stoffel et al.	2011	Mexico	<i>Pinus hartwegii</i>	24	86	63	1924-2008	4300	increment cores, stem discs	Return period
Šilhán et al.	2012	Ukraine	<i>Pinus nigra</i> ssp. <i>Pallasiana</i>	114	456	703	1780-2009	1200	increment cores	\
Trappmann and Stoffel	2013	Austria	<i>P. abies</i> , <i>F. sylvatica</i>	83	194	1417	1819-2009		increment cores, scar count	Return period
Corona et al.	2013	Switzerland	<i>L. decidua</i> , <i>Betula pendula</i> , <i>Corylus avellana</i> L., <i>Fraxinus</i> sp., <i>Sorbus aria</i> (L.) Crantz	133	229	737	1990-2011	1400	increment cores, scar count	Injuries/tree
Trappmann et al.	2014	Switzerland	<i>B. pendula</i> Roth, <i>L. decidua</i> Mill., <i>Populus tremula</i> , <i>P. abies</i> Karst., <i>Fraxinus excelsior</i> , <i>Salix caprea</i> , <i>A. pseudoplatanus</i> , <i>Alnus incana</i> , <i>S. aucuparia</i> , <i>Corylus avellana</i> , <i>S. aria</i> Crantz, <i>Prunus avium</i>	1260	202	488	unknown	1400	increment cores, scar count	Frequency
Morel et al.	2015	Switzerland	<i>L. decidua</i>	314	616	372	1908-2014	1800	increment cores, scar count	Frequency
Favillier et al.	2015	France	<i>A. opalus</i> , <i>Q. pubescens</i>	848	0	1230	unknown	600	scar count, forest inventory	Recurrence interval
Trappmann and Stoffel	2015	Switzerland	<i>L. decidua</i>	217	0	217	unknown	1610-2240	scars count	\
Corona et al.	2017	France	<i>A. opalus</i> , <i>Q. pubescens</i>	1004	0	1495	unknown	600	scar count, forest inventory	Injuries/cluster
Franco Ramos et al.	2017	Mexico	<i>Pinus hartwegii</i>	110	212	108	1780-2011	4000	increment cores	Return period
Favillier et al.	2017	France	<i>A. opalus</i> , <i>Q. pubescens</i>	1004	0	1495	unknown	600	scar count, forest inventory	Recurrence interval
Our study	2019	France	<i>A. alba</i> , <i>P. abies</i> , <i>U. glabra</i> , <i>A. pseudoplatanus</i> , <i>S. aria</i> , <i>F. sylvatica</i>	278	1097	810	1801-2017	1350-1490	scar count, forest inventory, increment cores	Recurrence interval

Tab. 1. Synthesis of rockfall reconstructions based on classical tree-ring analysis and the visual scar counting approach.

Growth disturbances	All GD dated		No corresponding damage on stem	
	Number	%	Number	%
Injuries	446	55	92	38
TRD	198	24	76	31
Growth suppression	133	16	63	26
Reaction wood	9	1	5	2
Growth release	24	3	7	3
Total GD	810	100	243	100

Tab. 2. Overview of growth disturbances (GD) identified in tree-ring series. TRD = tangential rows of traumatic resin ducts.