# A New Tree-Ring-Based, Semi-Quantitative Approach for the Determination of Snow Avalanche Events: use of Classification Trees for Validation

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## Abstract

On forested paths, dendrogeomorphology has been demonstrated to represent a powerful tool to reconstruct past activity of avalanches, an indispensable step in avalanche hazard assessment. Several quantitative and qualitative approaches have been shown to yield reasonable event chronologies but the question of the completeness of tree-ring records remains debatable. Here, we present an alternative semi-quantitative approach for the determination of past snow avalanche events. The approach relies on the assessment of the number and position of disturbed trees within avalanche paths as well as on the intensity of reactions in trees. In order to demonstrate that no bias was induced by the dendrogeomorphic expert, we carry out a statistical evaluation (Classification and Regression Trees, or CART) of the approach. Results point to the consistency and replicability of the procedure and to the fact that the approach is not restricted to the identification of high-magnitude avalanches. Evaluation of the semi-quantitative approach is illustrated on a well-documented path in Chamonix, French Alps. For the period 1905–2010, comparison between the avalanche years recorded in a substantial database (Enquête Permanente sur les Avalanches, or EPA) and those defined with dendrogeomorphic techniques shows that the avalanche record reconstructed from tree-ring series contains 38% of the observed events.

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## Introduction

Documenting past avalanche activity represents an indispensable step in avalanche hazard assessment (Ancey, 2004). Nevertheless, (i) archival records of past avalanche events do not normally yield data with satisfying spatial and temporal resolution, and (ii) precision concerning runout distance (Lied and Bakkehoi, 1980; McClung, 1999; Casteller et al., 2008) and/or avalanche type is generally poorly defined (Corona et al., 2012). In addition, (iii) historic documentation is most often biased toward events that caused damage to structure or loss of life on the one hand, and (iv) events are undersampled in unpopulated areas on the other hand (Bollschweiler et al., 2011).

On forested paths, dendrogeomorphology (Alestalo, 1971; Stoffel et al., 2010) has been demonstrated to represent a powerful tool to reconstruct past activity of avalanches with annual resolution and for periods covering past decades to centuries (Butler and Sawyer, 2008). External scars, reaction wood, growth asymmetry, and tangential rows of traumatic resin ducts have been the most frequently used avalanche indicators since they allow the dating and determination of multiple events from the same tree (Luckman, 2010). As all of these growth disturbances (hereafter referred to as GDs) vary in their expression within the tree (e.g. duration, radial encompassment, and degree of development), a series of graduated classes allows a discrimination of features that are clearly associated with avalanche activity so as to differentiate them from disturbances which can be induced by a variety of other, non-geomorphic factors (Corona et al., 2012). Different empirical rating systems have been proposed and improved in the past 10 years (Dubé et al., 2004; Reardon et al., 2008; Corona et al., 2012), but the question of how accurately an event or a time series of events can be reconstructed from tree-ring records remains debatable.

Some authors have used quantitative methods based on the proportion of disturbed trees (i.e. index number) to date an event in a given year (Butler and Sawyer, 2008). Dubé et al. (2004), Germain et al. (2005), Pederson et al. (2006), and Reardon et al. (2008) used an index number but also took into account the total number of disturbed trees. Conversely, Stoffel et al. (2006) used a qualitative approach where the nature and spatial distribution of trees with GDs were analyzed visually to determine years with avalanche activity. These approaches have provided reasonable event chronologies. Nevertheless, as Corona et al. (2012) emphasized, quantitative methods tend to underestimate activity due to the very stringent and arbitrary thresholds used that are better adapted to the determination of high-magnitude events. On the other hand, qualitative approaches may be very useful in cases with


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a limited sample depth, either on temporal or on spatial domains, depending strongly on the context at the site (Luckman, 2010).

Recently, Corona et al. (2012) evaluated the potential of tree-ring records to produce a dendrogeomorphic time series on an extensively and accurately documented avalanche path in the Chamonix valley (French Alps). The authors defined optimal values for the number of GDs and the index number, such that the match between avalanches documented in archival data (Enquête Permanente sur les Avalanches, hereafter referred to as EPA [see Historical Archives below]) and those observed in the tree-ring records was maximized. Their study pointed out the importance of a large sample depth (~100 trees) and suggested adaptation of the thresholds (related to the index number and the number of disturbed trees) with increasing/decreasing sample depth. However, the thresholds they used depend on the nature and amount of data gathered in this particular path and cannot be applied to other sites.

To compensate for these difficulties, a semi-quantitative approach is developed in this paper. The aim of this study, therefore, was (i) to promote this new approach for the determination of past snow avalanche years based on the analytical skills of the dendrogeomorphic expert; (ii) to demonstrate its consistency and replicability using a Classification and Regression Trees (CART) approach; (iii) to highlight the high potential of this approach in terms of past avalanche activity reconstruction; and (iv) to validate its reliability in a very well-documented path.


**FIGURE 1. Location of the three study sites (Pèlerins, Ressec, and Château Jouan paths) in the French Alps.**

## Study Area and Historical Archives

This study was conducted in the French Alps, in the Rhône-Alpes and Provence-Alpes-Côte d'Azur regions. Three avalanche paths were selected, the Pèlerins path near Chamonix-Mont-Blanc (Haute-Savoie), the Ressec path near Lanslevillard (Savoie), and the Château Jouan path near Montgenèvre (Hautes-Alpes; Fig. 1).

### *PELERINS PATH*

The Pèlerins avalanche path on the north-facing slope of the Arve Valley dominates the hamlet of Les Pèlerins, located 2 km southwest of downtown Chamonix (Table 1). It passes under the Aiguille du Midi cable car (Les Pèlerins-La Para), which was constructed for the first Winter Olympics in 1924. Snow avalanches are commonly triggered from a starting zone located between 3650 and 2750 m a.s.l. where an orthogneissic rockwall is partly covered by the Pèlerins glacier. The access road to the Mont Blanc Tunnel crosses the runout zone several times below 1275 m a.s.l. (Fig. 2, part a). This tunnel is a major north-south connection for Europe, and two million vehicles use this road each year, of which 33% are trucks (Corona et al., 2012).

The inner zone of the track is colonized by dense shrubs and shade-intolerant pioneer tree species with flexible stems. Toward the outer zone, European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.) are becoming dominant. Located in the upper mountain stage, the runout zone is covered by a dense forest dominated by *P. abies*. According to the data from the nearby meteorological station of Chamonix (1054 m a.s.l.), the annual (DJF) temperature is 6.6 °C (−2.5 °C) for the period 1935–1990, and the annual (DJF) precipitation amounts to 1262 mm (311 mm) for the period 1934–1990.

### *RESSEC PATH*

The Ressec avalanche path on the north-facing slope of the Arc Valley dominates the hamlet of Chantelouve, located 3 km

**TABLE 1**

**Site-related characteristics in the Pèlerins, Ressec, and Château Jouan paths. The three paths exhibit quite different features although their solar exposure and mean slope are rather similar. The Pèlerins path represents a very extended avalanche path, while the Ressec and Château Jouan paths are smaller in size.**

| Path name | Maximum elevation (m) | Minimum elevation (m) | Path length (m) | Mean slope angle (degrees) | Starting zone area (ha) | Runout zone area (ha) | Solar exposure |
|---|---|---|---|---|---|---|---|
| Pèlerins | 3650 | 1085 | 4900 | 35 | 110 | 70 | north |
| Ressec | 3060 | 1770 | 2550 | 30 | 55 | 15 | north |
| Château Jouan | 2500 | 1700 | 1700 | 29 | 12 | 7 | north |

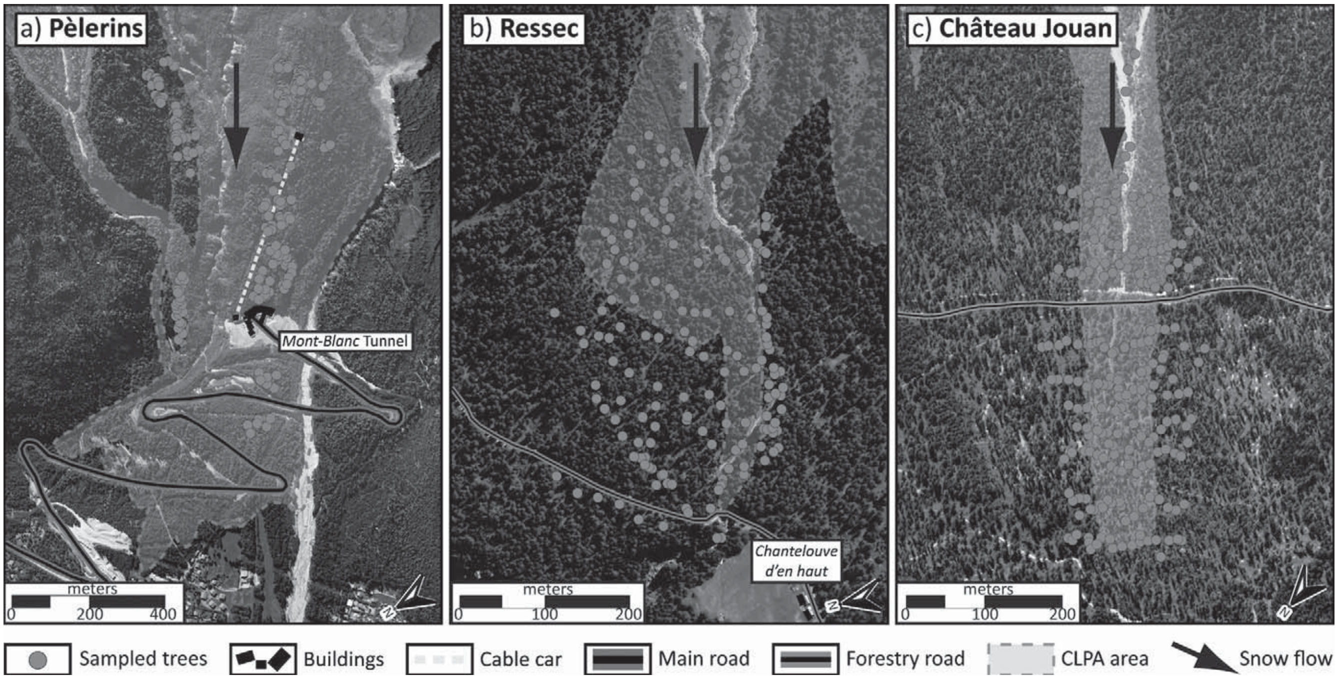


**FIGURE 2. Location of sampled trees in the (a) Pèlerins, (b) Ressec, and (c) Château Jouan snow avalanche paths. The CLPA (Carte de Localisation des Phénomènes d'Avalanche) represents historical spatial limits of snow avalanches derived from technical reports and photographs.**

northeast of downtown Lanslevillard (Table 1). Snow avalanches are commonly triggered from a starting zone located between 3060 and 2300 m a.s.l. A 5-m-deep ephemeral torrent that cuts into the runout zone may have a channelizing effect on snow avalanches (Fig. 2, part b).

The avalanche path is located in a zone composed of lustrous schists resulting in particularly poor soils. As a consequence, woody vegetation is mostly absent above 2000 m a.s.l., except for a few pioneering *L. decidua*. The runout zone is covered by a dense forest dominated by *P. abies* and *L. decidua*; silver fir (*Abies alba* Mill.) is scarce (1%). The nearby meteorological station of Lanslebourg-Mont-Cenis (1720 m a.s.l.) indicates annual (DJF) temperatures of 2.4 °C (−4.3 °C) and annual (DJF) precipitation of 995 mm (393 mm) for the period 1959–1973.

### *CHÂTEAU JOUAN PATH*

The Château Jouan avalanche path on the north-facing slope of the Durance Valley is located 2 km southwest of downtown Montgenèvre (Table 1). Snow avalanches are commonly triggered from a starting zone located between 2500 and 2000 m a.s.l.

The path of Château Jouan is located in a zone composed of Triassic dolomites and limestones. *L. decidua* is the only tree species present in this area (Fig. 2, part c). According to the data from the nearby meteorological station of Briançon (1212 m a.s.l.), annual (DJF) temperature was 8.0 °C (0.4 °C), and the annual (DJF) precipitation amounted to 755 mm (174 mm) for the period 1970–2004.

### *HISTORICAL ARCHIVES*

In France several documentary sources provide information about past snow avalanche events. In the EPA, the avalanche history of ~3900 recognized paths in the French Alps and the Pyrenees with a length >200 m is recorded since the early 20th century at most sites (Mougin, 1922). However, only avalanche events reaching a determined observation threshold have to be recorded. The EPA therefore represents a very substantial database and provides a huge quantity of information about past snow avalanches. These data have proved useful for risk assessment at the local (Eckert et al., 2007, 2010a) and regional scales and for the quantification of inter-annual variation of avalanche activity (Eckert et al., 2009, 2010b). EPA records are usually complemented with a map (Carte de Localisation des Phénomènes Avalancheux, hereafter referred to as CLPA) in which the release zones and maximal runout extent for different types of snow avalanches are recorded. Additional information can be found in other archives such as technical reports, aerial and terrestrial photographs, incidental narratives, diaries, municipal archives, and paintings (Corona et al., 2012).

As a result of the potential threat to infrastructure, the Pèlerins avalanche path has received considerable attention in the past, and activity has been documented continuously and with unusual accuracy, especially since the beginning of the 20th century. In total, 47 avalanche years have been documented for the period 1779–2010, with most of them (37) during the EPA time extent 1905–2010. Conversely, the Ressec and Château Jouan paths only threaten forestry roads which are used by a very limited number of people during winter season. As a result, 20 and 19 events, respectively, have been recorded in the EPA in these two paths for the period 1907–2010. The lack of a significant element at risk may have led to a less accurate survey in these areas, especially during the first half of the 20th century, indicating that the real activity was certainly largely underestimated. No other historical archives have been found for these two avalanche paths.

## Tree-Ring-Based Snow Avalanche Event Chronologies

### *DENDROGEOMORPHIC ANALYSIS*

For this study, sampling areas were restricted to the lower track and runout zone of the paths. The goal was to maximize the likelihood of identifying the maximal extent of avalanche events. Based on the CLPA, we also aimed to select trees close to the recorded lateral limits. All samples were extracted from conifers (*L. decidua*, *P. abies*, and *A. alba*). We used impact scars (Trappmann and Stoffel, 2013; Corona et al., 2013), the appearance of callus tissue (Schneuwly et al., 2009a, 2009b) and tangential rows of traumatic resin ducts (referred hereafter as to TRD; Bollschweiler et al., 2008; Stoffel, 2008; Stoffel and Hitz, 2008), the initiation of compression wood (Timell, 1986), and abrupt growth reductions (Butler and Malanson, 1985) to determine the potential occurrence of avalanches. Selection of trees, sampling design as well as sample preparation and analysis followed the procedures well described in Stoffel and Bollschweiler (2008).

### *DETERMINATION OF SNOW AVALANCHE YEARS*

In a next step, intensities were assigned to GDs in order to emphasize features that are clearly associated with avalanche activity and to discriminate these from disturbances possibly induced by other factors (such as creeping snow, strong wind, etc.). We used a rating system (Table 2) similar to those described in the recent literature (Germain et al., 2005; Reardon et al., 2008; Corona et al., 2012) and based on the visual quality of the evidence of reactions within each sample. With such an intensity scale, we assigned significant weight (classes 4 and 5) to GDs that were initiated by strong external forces directly related to avalanche flows. Class 3 is an intermediate category mainly used for compression wood which was clearly visible in the samples but which could, under certain circumstances, stem from other processes (i.e. creeping snow). Classes 1 and 2 point to reactions in the wood which can stem from disturbances but where an unambiguous attribution to a snow avalanche was not possible (Table 2).

TABLE 2

**Growth disturbance intensity scale. This scale emphasizes features that are clearly associated with avalanche activity and discriminates against disturbances that may be induced by other factors. Thresholds related to growth reduction and compression wood have been defined based on the visual quality of these reactions within each sample.**

| Intensity | Growth disturbances characterization |
|---|---|
| Class 5 | Impact scars or dense TRD which can undoubtedly be associated with a scar. |
| Class 4 | Obvious TRD (with some gaps in the rows), presence of callus tissue, obvious compression wood being formed for more than 3 successive growth years or abrupt growth reduction lasting for at least 5 years (associated with stem breakage). |
| Class 3 | Obvious compression wood being formed for 1–3 successive growth years following disturbance. |
| Class 2 | Compression wood present but not well defined or growth reduction lasting for less than 5 years. |
| Class 1 | Scattered TRD. |

TRD = tangential rows of traumatic resin ducts.

GD data from individual trees were then summarized in a geographic information system with ArcGIS (ESRI, 2012). For each year of the chronology, trees that were living (i.e. trees that were present in a given year considering their age as obtained from sample analysis) were plotted according to their geographic coordinates. Disturbed trees were highlighted using a color gradient corresponding to the intensity of reaction. However, only disturbances of intermediate or strong intensity (classes 3–5) were considered for avalanche year assessment. As mentioned before, intensity classes 1 and 2 could not unambiguously be attributed to snow avalanche activity. The determination of snow avalanche years was based on a visual evaluation of the resulting maps and focused on several assessment criteria.

In the expert approach, each map (one per chronology year) was assessed separately by analyzing simultaneously the number of disturbed trees present, the proportion of strong intensity GDs (which are undoubtedly related to past avalanche activity) compared to intermediate ones as well as their distribution within the path. A minimum of three disturbed trees was required for a year to be qualified as an avalanche year. This threshold aimed at minimizing the risk that one or two GDs caused by other factors (possible influence of felling activity, scars induced by ungulate browsing) could mistakenly be attributed to avalanches. Years showing several GDs of strong intensity were unequivocally identified as avalanche years. For years where only a few disturbed trees were observed, special attention was given to spatial criteria, thus allowing the expert to determine whether the pattern was clustered or scattered. This allowed distinction between years with a dispersed pattern of reacting trees, where disturbance was not apparently induced by snow avalanches, and years where disturbed trees were grouped on the slope and thus attested to the occurrence of an avalanche. In the latter cases, only years with disturbed trees located in the upper track were assessed as avalanche years. Conversely, years showing a few disturbed trees in the runout zone but very few or no GDs in the trees located higher in the track were not considered avalanche years. This was justified by the fact that all avalanches that disturbed trees in the runout zone should also have been recorded in some of the trees located in the upper track. Thus, although the assessment of avalanche years resulted from an evaluation of criteria based on field knowledge, the expert remained as objective as possible when assigning a score (*avalanche/non-avalanche*) to each year of the chronologies.

### *GROWTH DISTURBANCES AND PAST AVALANCHE ACTIVITY*

Sampling campaigns were carried out during the summers of 2010 and 2011. A total of 209, 168, and 210 trees, respectively, were sampled in the Pèlerins, Ressec, and Château Jouan paths (Fig. 2, parts a, b, c). The samples from the Pèlerins path were those analyzed by Corona et al. (2012). All GDs observed in the latter path were reclassified according to the rating system used in the present study (Table 2). Sample analysis permitted identification of 660, 591, and 491 GDs, respectively (Table 3). In the Pèlerins path, growth reductions were the most frequently observed type

**TABLE 3**

**Sample depth, (a) types, and (b) intensity of growth disturbances in the Pèlerins, Ressec, and Château Jouan paths.**

| | | PELERINS | | RESSEC | | CHÂTEAU JOUAN | |
|---|---|---|---|---|---|---|---|
| | Sample analysis | Number | Percentage | Number | Percentage | Number | Percentage |
| | **Sampled trees** | **209** | **—** | **168** | **—** | **210** | **—** |
| | **Sample type** | **452** | **100%** | **401** | **100%** | **438** | **100%** |
| | Cross section | 0 | 0% | 59 | 15% | 63 | 14% |
| | Increment core | 452 | 100% | 342 | 85% | 375 | 86% |
| | **Growth disturbances** | **660** | **100%** | **591** | **100%** | **491** | **100%** |
| a | Impact scars | 0 | 0% | 28 | 5% | 35 | 7% |
| | TRD | 115 | 17% | 251 | 42.5% | 229 | 46.5% |
| | Compression wood | 150 | 23% | 155 | 26% | 156 | 32% |
| | Growth reduction | 368 | 56% | 155 | 26% | 63 | 13% |
| | Callus tissue | 27 | 4% | 2 | 0.5% | 8 | 1.5% |
| b | Intensity class 5 | 142 | 22% | 69 | 11.5% | 49 | 10% |
| | Intensity class 4 | 219 | 33% | 140 | 23.5% | 183 | 36.5% |
| | Intensity class 3 | 50 | 8% | 105 | 18% | 66 | 13% |
| | Intensity class 2 | 240 | 36% | 195 | 33% | 110 | 22% |
| | Intensity class 1 | 9 | 1% | 82 | 14% | 83 | 18.5% |

TRD = tangential rows of traumatic resin ducts.

of GD (56%), whereas TRD were predominantly identified in the Ressec (42.5%) and Château Jouan (46.5%) paths. Concerning GD intensity, class 2 was predominant in the Pèlerins (36%) and Ressec (33%) paths. By contrast, class 4 was most present (36.5%) in the Château Jouan path (Table 3).

Based on the procedure described in the previous section, 34 avalanche years were reconstructed in the Pèlerins path for the past 240 years (1771–2010). In the Ressec and Château Jouan paths, a total of 24 and 17 avalanche years have been identified for the period 1870–2010 and 1799–2010, respectively.

## Statistical Evaluation of the Semi-quantitative Approach

### *CLASSIFICATION TREES AND CHARACTERIZATION OF ASSESSMENT CRITERIA*

The semi-quantitative approach used for the determination of snow avalanche years is based on a dendrogeomorphic expert approach. Each year of the tree-ring chronology is assessed in a similar way and based on the same criteria. To demonstrate that no bias is introduced by the expert, we assessed the consistency of approach statistically. For this purpose, a Classification and Regression Tree (hereafter referred to as CART; Breiman et al., 1984; Ripley, 1996) approach was used. CART is a statistical tree-building technique that explains the variation of a response variable using a set of explanatory independent variables, so-called predictors. The method is based on a recursive binary splitting of the data into mutually exclusive subgroups within which objects have similar values for the response variable. At each split, the CART imposes a ''goodness of split criterion,'' similar to the method of least squares, so as to optimize splitting for each variable and ultimately minimize the overall probability of misclassifying the response variable. The CART adds variables until classification trees have grown to a maximum size and, in the final step, removes the variables that do not add any predictive power to the model. This allows the CART to select the best model adjusting the number of variables used in the analysis (for more details see Breiman et al., 1984).

In the present work, the response variable was characterized by the score assigned by the dendrogeomorphic expert during its assessment. Each year of the three tree-ring chronologies was thus classified as an *avalanche* or *non-avalanche* year. Explanatory variables were then characterized based on the assessment criteria. The first variable chosen was $GD_{tot}(t)$, i.e. the total number of GDs (classes 3 to 5) in each year $t$. We then calculated $GD_i(t)$, i.e. the number of GDs from each class of intensity $i$, in each year $t$. To have an idea of the proportion of GDs from each class related to the total number of GDs present in a given year, we computed:

$$GD_i^*(t) = GD_i(t)/GD_{tot}(t). \tag{1}$$

As both sample depth and the number of GDs decrease in the past, a standardization procedure was applied to take account of all values in the data set and to avoid potential bias in the data. We therefore included the annual standardized anomaly for each intensity class into the analysis:

$$GD_i'(t) = \left(GD_i(t) - \overline{GD_i}\right)/\sigma_i, \tag{2}$$

where

$$\overline{GD_i} = \sum_{t=1}^{T} GD_i(t)/T, \tag{3}$$

$$\sigma_i = \sqrt{\sum_{t=1}^{T} \left(GD_i(t) - \overline{GD_i}\right)^2 / T}, \tag{4}$$

and $T$ corresponds to the extent of each tree-ring chronology.

The last criteria on which the dendrogeomorphic expert focused for the determination of avalanche years were the position and spread of disturbed trees along the path. No universally applicable rule could be defined for the characterization of the different patterns of GD location. Therefore, spatial criteria were not used in the statistical evaluation of the approach.

### *CONSISTENCY OF THE APPROACH*

Considering the seven characterized explanatory variables ($GD_{tot}$, $GD_3^*$, $GD_4^*$, $GD_5^*$, $GD_3'$, $GD_4'$, $GD_5'$), we evaluated consistency of the scores assigned by the dendrogeomorphic expert to each year of the tree-ring chronologies. Practically, data from both the Pèlerins and Ressec paths were combined to create a sufficiently large and representative data set. Only years where at least one GD was present in the tree-ring record were considered, since, from a dendrogeomorphic perspective, years without GD could not show evidence of a snow avalanche event. The combined data set yielded data for 213 years. Using the ''rpart'' routine (Therneau and Atkinson, 1997) of the R package (R Development Core Team, 2007), the classification tree was calibrated with the scores assigned (*avalanche/non-avalanche* year) as a response variable and based on values resulting from the explanatory variables. To test the performance of the model, we then carried out repeated random subsampling validation, where the data set is randomly partitioned into training (90% of all years) and validation subsets (remaining 10%). For each of these splits, the model was fitted to the training subset, and predictive accuracy was assessed using the validation subset (Breiman et al., 1984; Kohavi, 1995). The results were then averaged over the splits for 100 iterations. Cross-validation classification probabilities indicated that the model correctly classified the years in 89% of the cases.

### *REPLICABILITY OF THE APPROACH BASED ON AN INDEPENDENT PATH*

Illustration of the replicability of our approach represented the last step of the statistical evaluation. This procedure was required to demonstrate that the expert's assessment does not depend on site-related characteristics of a given path and can therefore be applied elsewhere. We consequently applied the classification tree resulting from the above-mentioned combined data set (from both the Pèlerins and Ressec paths) to predict *avalanche/non-avalanche* years in an independent path. The calibrated model pointed to the prevalence of the total number of GDs in the assessment since the corresponding variable $GD_{tot}$ was the first classification split (Fig. 3). It also permitted to emphasize a hierarchy within the classification splits, from variables related to strong intensity ($GD_5^*$, $GD_5'$, ) to weaker ones ($GD_4^*$, $GD_3'$, $GD_3^*$).

Based on this classification tree, we predicted scores in the Château Jouan path. Comparison of the scores (*avalanche/non-avalanche* year) predicted and those initially assigned during assessment in this path was summarized in a confusion matrix. Results show that only 4 out of 128 years (3%) were incorrectly predicted (Table 4). A correct prediction means that the score assigned by the dendrogeomorphic expert is the same as the one

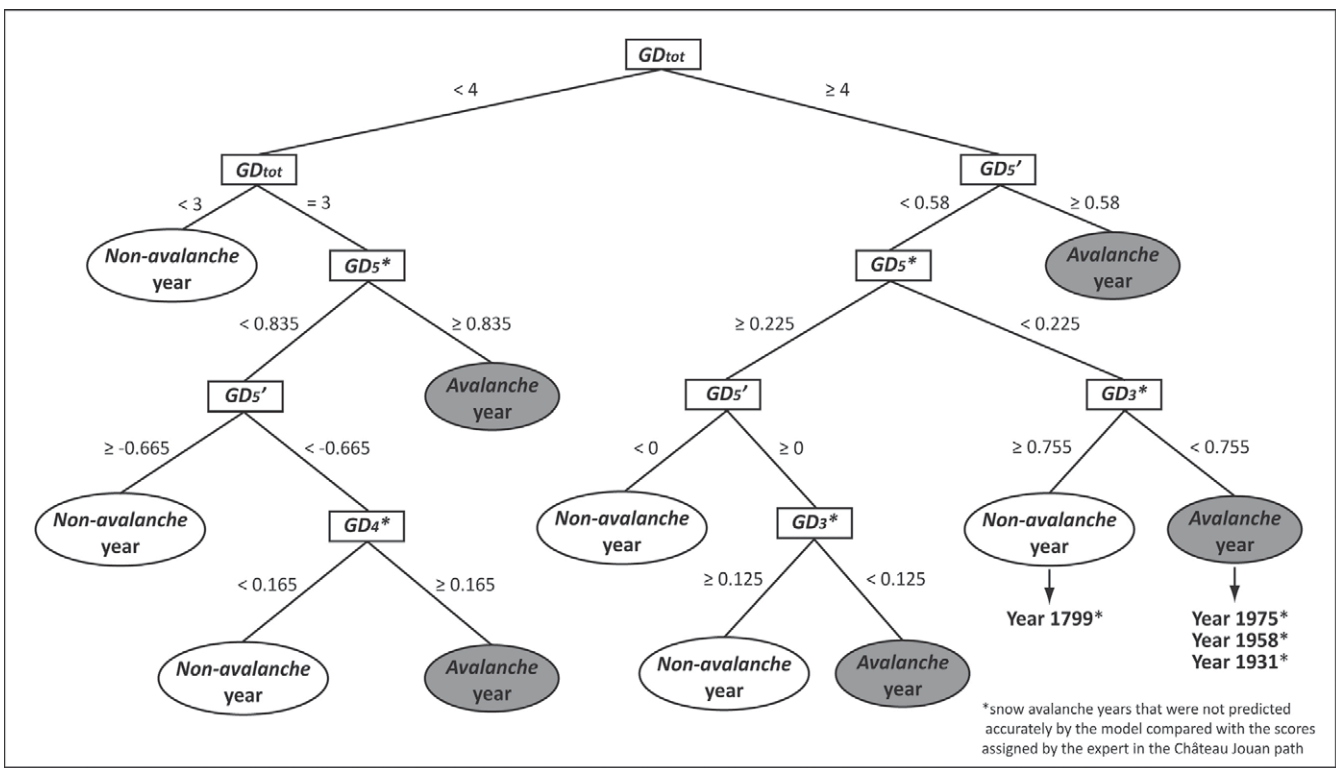


**FIGURE 3. Classification tree calibrated from a combined data set composed of tree-ring chronology years from both the Pèlerins and Ressec paths. It was used to predict scores (*avalanche/non-avalanche* years) in the Château Jouan path in order to demonstrate replicability of the semi-quantitative approach. GD = growth disturbances.**

**TABLE 4**

**Confusion matrix of assigned and predicted avalanche occurrences in the Château Jouan path. The dendrogeomorphic expert initially assigned scores during assessment procedure. Predicted values result from the classification tree calibrated from a combined data set composed of tree-ring chronology years from both Pèlerins and Ressec paths.**

| | | Scores predicted by the model | | Total |
|---|---|---|---|---|
| | | *non-avalanche* | *avalanche* | |
| Scores assigned by the expert | *non-avalanche* | 108 | 3 | 111 |
| | *avalanche* | 1 | 16 | 17 |
| % | *non-avalanche* | 97.3 | 2.7 | 100 |
| | *avalanche* | 5.9 | 94.1 | 100 |

predicted by the model. In fact, 3 years were considered *non-avalanche* years by the expert whereas the classification tree considered them as *avalanche* years (Figs. 3 and 4). Conversely, one year was considered an *avalanche* year during the expert's assessment and was predicted as *non-avalanche* year by the model (Figs. 3 and 4).

### *AN EFFICIENT TOOL TO COMPLEMENT HISTORICAL AVALANCHE CHRONOLOGIES*

The reliability of our procedure was tested at Pèlerins path where we compared results from dendrogeomorphic assessment with data recorded in the EPA and historical archives (Fig. 5). For the period covered by the EPA (1905–2010), our approach allowed reconstruction of 14 out of 37 (38%) documented years. Furthermore, four undocumented events have been identified in 1932, 1948, 1993, and 1995. In a second step, comparison was realized for the entire period covered with tree-ring records (1771–2010), for which 18 out of 47 (38%) documented events were reconstructed. A total of 16 avalanches could be added to the historical chronology (Fig. 5).

## Discussion and Conclusion

### *CONTRIBUTION OF THE SPATIAL INFORMATION IN AVALANCHE ASSESSMENT*

The use of tree rings for the reconstruction of chronologies of snow avalanching has been progressively recognized over the past decades and has become popular worldwide in the early 2000s with studies in Canada (Dubé et al., 2004; Germain et al., 2010), the Alps (Stoffel et al., 2006; Casteller et al., 2007; Corona et al., 2010, 2012, 2013; Kogelnig-Mayer et al., 2011), Pyrenees (Muntan et al., 2009), and South America (Casteller et al., 2011). Although all of these studies were based on the same fundamental dendrogeomorphic principles, the way to determine avalanche years as well as the criteria used varied strongly from one study to another, depending on the objective pursued. In our approach, we considered only GDs of intermediate and strong intensities for the identification of avalanche years. We therefore minimized the risk of introducing bias due to GDs which were caused by external factors.

Most of the authors selected the use of arbitrary quantitative thresholds (i.e., Butler and Sawyer, 2008; Germain et al., 2005; Reardon et al., 2008) and attempted to track high-magnitude events (Dubé et al., 2004; Germain et al., 2009), whereas Stoffel et al. (2006) used a qualitative approach and could therefore also reconstruct much smaller events with a more limited spatial extent. In the present study, we present an alternative semi-quantitative approach which integrally relies on the analytical skills of the dendrogeomorphic expert. This approach allows identification of different types of avalanche events independently from their size. Even if it might be considered as open to operator bias, we here demonstrate the objectivity of its results based on a statistical evaluation.

Cross-validation classification probabilities for a representative data set from the Pèlerins and Ressec paths, where different site characteristics prevail (Table 1), indicate that the model correctly classified the years in 89% of the cases. This attests the accuracy of classification tree predictions and consecutively demonstrates the good consistency of our procedure. In other words, it confirms that similar decisions were made during assessment of each year of the chronology. The classification tree calibrated with the representative data set emphasized the prevalence of a few variables such as $GD_{tot}$, $GD_5^*$, and $GD_5'$ (Fig. 3) and is reflective of the typical strategy of a dendrogeomorphic expert's approach. The number of GDs appears to be the first criterion considered, whereas strong intensity disturbances seem to be decisive as well.

Furthermore, we obtained a very satisfying match between scores (*avalanche*/*non-avalanche* years) predicted by the classification tree (Fig. 3) and those initially assigned by the dendrogeomorphic expert in the Château Jouan path. Only 4 out of 128 years (3%) were incorrectly predicted, and 16 out of the 17 *avalanche* years (94%) assessed by the expert were also predicted as *avalanche* years by the model (Table 4). During the expert's assessment, the years 1931, 1958, and 1975 were considered *non-avalanche* years since GDs were widely scattered in the path, which was already colonized by a large number of trees at that time (Fig. 4). Moreover, a very small number of trees were disturbed in the lower portions of the track during these years. By contrast, the model predicted these years as *avalanche* years based on (i) the number of GDs exceeding three ($GD_{tot} \geq 4$), (ii) the low scores for both variables related to intensity class 5 ($GD_5' < 0.58$ and $GD_5^* < 0.225$), as well as (iii) the proportion of GDs with intensity class 3 ($GD_3^*$) that was lower than 0.755 (Fig. 3). Conversely, the year 1799 was considered as an *avalanche* year during the expert's assessment while the classification tree did not confirm this choice. In this particular case, no disturbances were identified in the lower track where few living trees were present (Fig. 4). All disturbed trees were observed in the lower part of the runout zone and were clustered. Accordingly, and even if most of GDs were classified as intermediate intensity (class 3), it seemed justified to consider this case as an *avalanche* year. The high proportion of GDs with intensity class 3 ($GD_3^* \geq 0.755$) explained why the model predicted this year as a *non-avalanche* year (Fig. 3). Interestingly, the spatial component was decisive in all misclassified years, which seems logical given that spatial criteria could not be included in the statistical evaluation of our semi-quantitative approach. This finding emphasizes quite clearly the added value of the expert's assessment, especially for years where GDs patterns are equivocal, and the

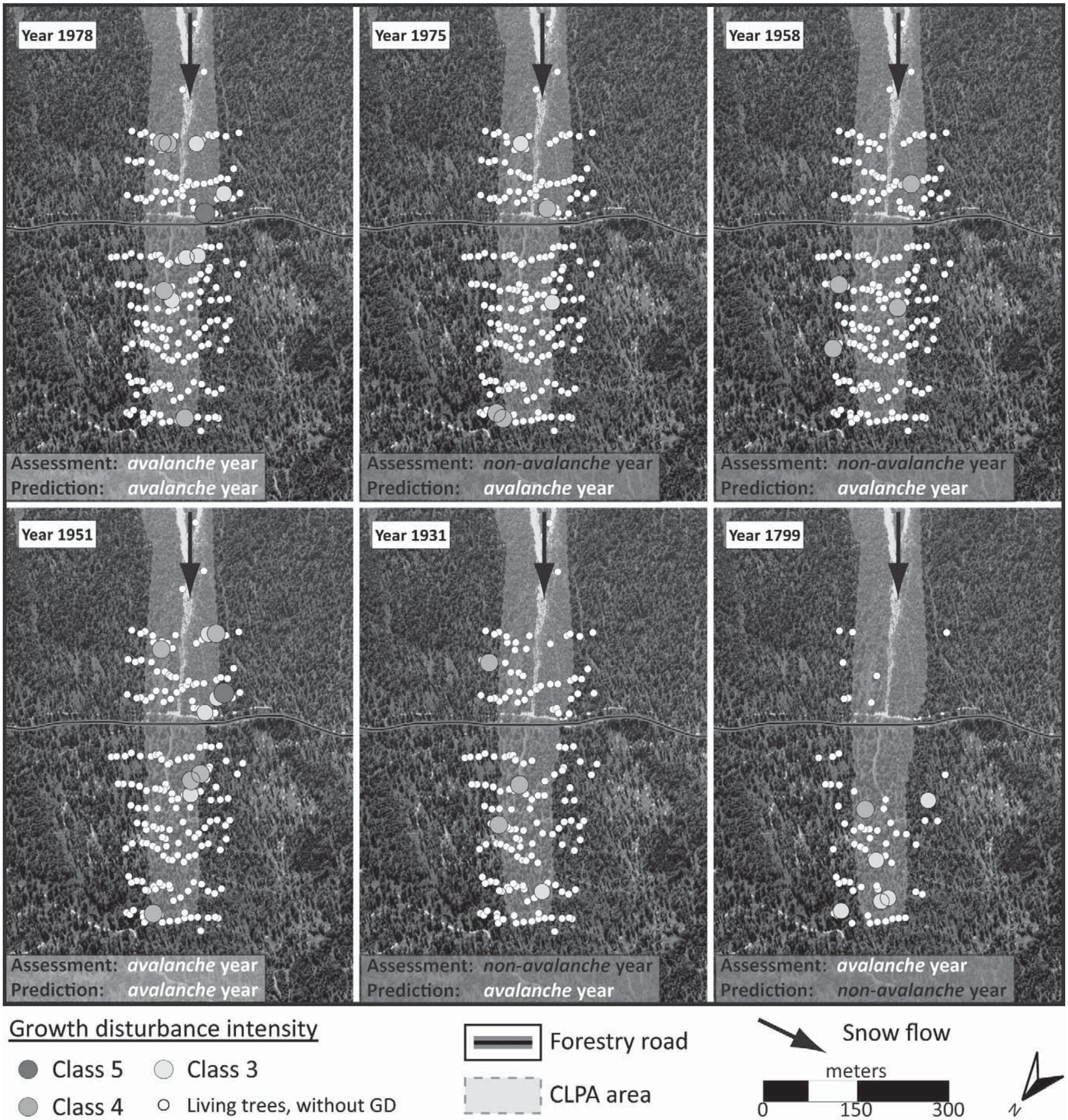


**FIGURE 4. Spatial distribution of disturbed trees for six years in the Château Jouan path. Initially, scores (*avalanche*/*non-avalanche* year) were assigned using ''expert procedures'' (see text for details). Scores were subsequently predicted using a classification tree calibrated from a combined data set composed of tree-ring chronology years from both the Pèlerins and Ressec paths. Two examples (1978 and 1951) represent years correctly predicted by the model. Conversely, four years (1975, 1958, 1931, and 1799) were incorrectly predicted. These represent only 3% of all predicted years. GD = growth disturbance. CLPA areas represent historical limits of snow avalanches derived from technical reports and photographs.**

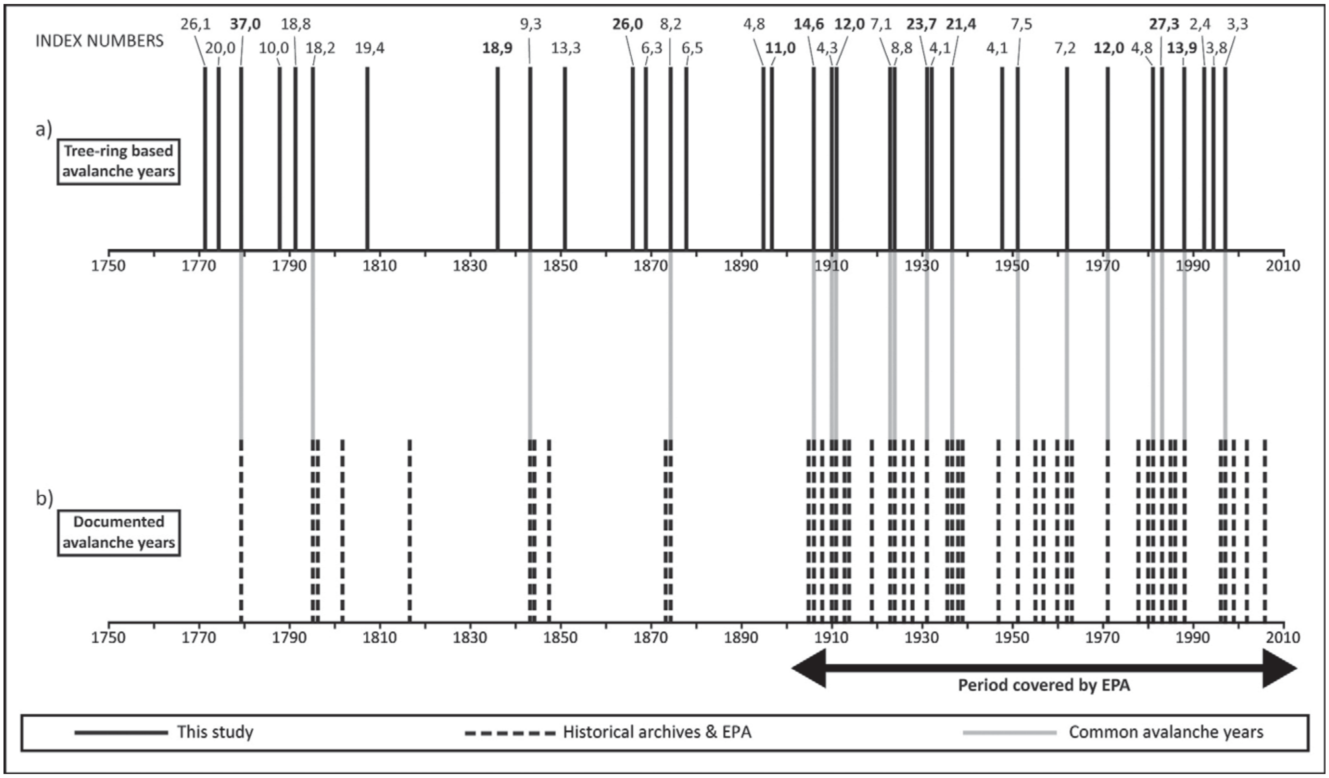


**FIGURE 5. Snow avalanche years in the Pèlerins path. Comparison of (a) tree-ring-based reconstructed years from this study with (b) documented avalanche years from historical archives and the Enquête Permanente sur les Avalanches (EPA) database. Index numbers correspond to the percentage of disturbed trees in a given year. Bold values emphasize years where both the fixed thresholds of growth disturbances (GDs) ≥ 10 and It ≥ 10 were reached. It = the proportion of disturbed trees (index number).**

necessity of further work devoted to the inclusion of spatial criteria into the CART modeling.

We therefore demonstrate that our semi-quantitative approach is replicable, considering the very good results from the CART approach (Table 4). However, since the data sets used in this study were quite small, the classification tree was rather sensitive. Hence, any modification in scores of the response variable may lead to a slightly different model. As a consequence, the classification tree presented in this work (Fig. 3) cannot be used in its raw state for the determination of past snow avalanche years in other paths without care. In the future, calibration of such a model using a larger data set with more avalanche paths could help to standardize dendrogeomorphic procedures and an improved determination of snow avalanche years.

### *A VALUABLE APPROACH FOR THE DETERMINATION OF PAST SNOW AVALANCHES*

As a result of the combined use of both quantitative (number of GDs in a given year) and qualitative criteria (intensity and array of GDs), our approach allowed identification of a large number of snow avalanche years in three avalanche paths of the French Alps. The reconstruction was not limited to large-extent events but also yielded data for smaller events (Fig. 6). In the well-documented Pèlerins path, 14 out of 18 events defined by our approach were also recorded in the archives of the EPA for period 1905–2010. Within the 4 undocumented years, 1948 and 1993 exhibited GDs only above 1720 m a.s.l. (Table 5). As the EPA observation threshold (located at 1540 m a.s.l. in this path) was not reached, these events were not recorded in the database. Conversely, both years 1932 and 1995 showed disturbed trees down to an elevation of 1470 m a.s.l., which is slightly below the observation threshold. These two events could have been missed since they stopped sufficiently far away from critical infrastructure and consequently did not represent any imminent threat in a context of risk management, or simply because the event was not observed by witnesses.

Given the exceptional accuracy of the available historical records in the Pèlerins path, we had a unique opportunity to quantify the reconstruction rate of the semi-quantitative approach. Considering the period covered by the EPA (1905–2010), we were able to reconstruct 38% of all documented avalanche years. Although this result might be considered surprisingly low, it is in agreement with the main conclusions of Corona et al. (2012). These authors applied a slightly different approach and concluded that the dendrogeomorphic reconstruction underestimates years with natural avalanche activity by roughly 60% in the Pèlerins path. Several reasons may be invoked that explain why snow avalanche reconstruction has to be seen as a minimum frequency of natural avalanches. The main limiting factor is that major disturbances (tilting, scarring) may mask the evidence of later events in the same tree. Hence, trees are not consistent recorders of evidence over time; i.e. the propensity to

**TABLE 5**

**Snow avalanche years reconstructed based on several assessment criteria in the Pèlerins path. This study reconstructed 34 event years for the period 1771–2010. In comparison, only 11 years (bold) would have been identified based on the fixed thresholds of GDs ≥ 10 and It ≥ 10 (Dubé et al., 2004; Reardon et al., 2008; Corona et al., 2012).**

| Snow avalanche years | | | Assessment criteria | | | | | Additionnal criterion |
|---|---|---|---|---|---|---|---|---|
| This study | Corona et al. (2012) | Historical archives | Total number of GDs | GDs Intensity class 5 | GDs Intensity class 4 | GDs Intensity class 3 | Runout altitude (m, tree-ring) | Index number |
| 1997 | | x | 7 | 4 | 1 | 1 | 1570 | 3.3 |
| 1995 | | | 8 | 6 | 1 | 0 | 1470 | 3.8 |
| 1993 | | | 5 | 3 | 0 | 1 | 1720 | 2.4 |
| **1988** | x | x | **29** | 9 | 5 | 6 | 1530 | **13.9** |
| **1983** | x | x | **57** | 10 | 31 | 1 | 1180 | **27.3** |
| 1981 | x | x | 10 | 1 | 1 | 3 | 1740 | 4.8 |
| **1971** | x | x | **25** | 6 | 9 | 0 | 1280 | **12.0** |
| 1962 | x | x | 15 | 1 | 10 | 0 | 1450 | 7.2 |
| 1951 | x | x | 15 | 6 | 1 | 0 | 1460 | 7.5 |
| 1948 | | | 8 | 5 | 2 | 1 | 1760 | 4.1 |
| **1937** | x | x | **37** | 4 | 9 | 0 | 1330 | **21.4** |
| 1932 | x | | 7 | 2 | 4 | 0 | 1470 | 4.1 |
| **1931** | x | x | **40** | 5 | 18 | 5 | 1330 | **23.7** |
| 1924 | x | x | 14 | 5 | 3 | 2 | 1470 | 8.8 |
| 1923 | x | x | 11 | 8 | 2 | 0 | 1450 | 7.1 |
| **1911** | x | x | **17** | 3 | 8 | 0 | 1470 | **12.0** |
| 1910 | | x | 6 | 3 | 3 | 0 | 1780 | 4.3 |
| **1906** | x | x | **20** | 7 | 6 | 1 | 1450 | **14.6** |
| **1897** | x | | **14** | 3 | 4 | 0 | 1320 | **11.0** |
| 1895 | | | 6 | 1 | 4 | 0 | 1640 | 4.8 |
| 1878 | x | | 6 | 0 | 3 | 1 | 1590 | 6.5 |
| 1874 | x | x | 7 | 2 | 2 | 0 | 1810 | 8.2 |
| 1869 | x | | 5 | 2 | 2 | 0 | 1780 | 6.3 |
| **1866** | x | | **20** | 2 | 13 | 0 | 1340 | **26.0** |
| 1851 | x | | 8 | 1 | 2 | 0 | 1780 | 13.3 |
| 1843 | x | x | 5 | 0 | 1 | 2 | 1740 | 9.3 |
| **1836** | x | | **10** | 0 | 6 | 0 | 1760 | **18.9** |
| 1807 | x | | 7 | 1 | 2 | 3 | 1740 | 19.4 |
| 1795 | x | x | 6 | 0 | 4 | 0 | 1780 | 18.2 |
| 1791 | x | | 6 | 0 | 4 | 1 | 1740 | 18.8 |
| 1788 | | | 3 | 0 | 1 | 2 | 1730 | 10.0 |
| **1779** | x | x | **10** | 3 | 1 | 0 | 1750 | **37.0** |
| 1774 | x | | 5 | 0 | 3 | 0 | 1740 | 20.0 |
| 1771 | x | | 6 | 0 | 1 | 2 | 1780 | 26.1 |

GDs = growth disturbances.
It = proportion of disturbed trees (index number).

record damage varies with the age and size of the tree (Luckman, 2010).

In order to highlight the strength of our approach for the determination of snow avalanche years, we followed a purely quantitative *a posteriori* method used in recent studies (e.g. Reardon et al., 2008; Corona et al., 2010). Thresholds related to the total number of GDs ($n \geq 10$) and the percentage of disturbed trees (index number ≥ 10) in a given year were applied to the tree-ring data from the Pèlerins path. In contrast to the strategy used in our semi-quantitative approach, the five intensity classes were considered here. Results showed that only 11 years were identified for the period 1771–2010 (Fig. 5 and Table 5). Hence, compared to the 34 years identified with the expert's approach, the total number of reconstructed events is reduced drastically if the fixed quantitative thresholds are being applied without any consideration of the spatial patterns of reacting trees. Furthermore, 3 years exhibited quite singular GD arrays (1836, 1911, and 1988). Most GDs in these years were located in the track but (almost) none in the runout zone (Fig. 6). Considering the total number of GDs and index number varying between 10 and 29 and between 12% and 19%, respectively (Fig. 5 and Table 5), these years would have been considered high-magnitude events in terms of damage (e.g., Dubé et al., 2004; Germain et al., 2009). Interestingly, these years do not correspond to large-extent events based on the position of GDs within the path

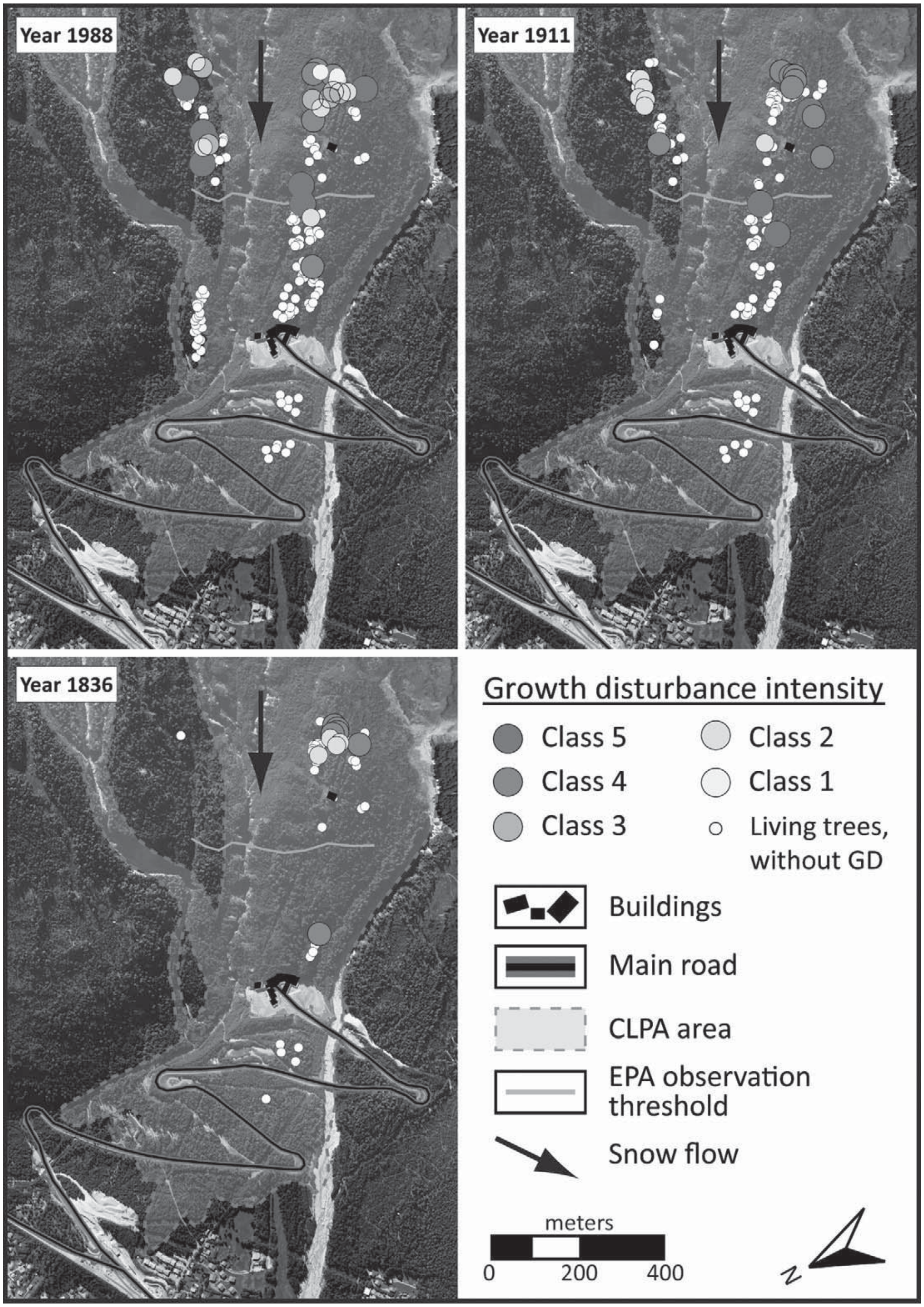


**FIGURE 6. Spatial distribution of disturbed trees in the Pèlerins path in 1836, 1911, and 1988. Note that only avalanches reaching a determined observation threshold are recorded in the EPA database. For discussion, see text. GD = growth disturbance. CLPA defined in Figure 2, EPA in Figure 5.**

and compared to historical limits derived from technical reports and photographs (CLPA) as well as the EPA observation threshold (Fig. 6).

All in all, this paper highlights the contribution of semi-quantitative approaches for the determination of past snow avalanche years. The approach presented in this study is a valuable tool in snow avalanche hazard assessment, especially where there is little or no historical data available.

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