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# One and a half century of avalanche risk to settlements in the upper Maurienne valley inferred from land cover and socio-environmental changes.

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## Abstract

Changes in mountain landscape can affect avalanche activity, causing changes in risk, potentially enhanced by a transition of the socio-environmental system and its underlying dynamics. Thus, integrative approaches combining biophysical and social sciences are required to assess changes in risk in all its dimensions. This study proposes a holistic methodology combining land cover change detection using advanced image processing techniques, geo-historical investigations and qualitative modelling of risk changes in order to infer the evolution of avalanche risk and its drivers in the upper Maurienne (French Alps) from 1860 to 2017. Results show that a continuous increase of forested areas associated with the retraction of agro-pastoral zones followed a period of land abandonment and depopulation. However, reforestation within avalanche paths remains largely incomplete and mostly absent in the majority of release areas, making a decrease in avalanche occurrence and propagation unlikely. This, combined with marked urban sprawl partially concentrated in avalanche prone areas, locally increased the exposure of residential settlements to avalanches. Hence, even if new defense structures have been set up, our analysis indicates that avalanche risk in the upper Maurienne increased through the study period. Even if local specificity related to physical dissimilarities and/or distinguished socio-economic trends always exist, our results may be valid for many high alpine valleys. Our approach is also transferable to other natural hazards, notably in wider mountain environments, as a contribution to the elaboration of effective adaptation strategies in a context of increasing risks related to combined climate change and socio-economic transitions.

*Keywords:* avalanche risk, exposure, diachronic analysis, land cover changes, geohistory

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## 1. Introduction

Snow avalanches are prevalent in mountain areas. The natural process is characterized by a rapid snow flow (Hopfinger, 1983; Schweizer et al., 2003). Snow avalanches are naturally triggered by a combination of factors such as weather conditions (temperature, snowfall, wind direction, etc.), slope, surface roughness (McClung & Schaerer, 2006; Bebi et al., 2009) and seismic activity (Podolskiy et al., 2010; Kargel et al., 2016). The sudden nature of the phenomena and the complexity of the interaction between the triggering factors endanger people, buildings and infrastructures, causing damages and fatalities all over Alpine environments (e.g. Berlin et al. (2019); Höller (2007); Rapin & Ancey (2000)). Worldwide rise of losses due to natural disasters e.g. floods, snow avalanches etc., and, more widely, the need to take socio-economic considerations into account in mitigation approaches pushed forward the emergence of the concept of risk in the natural hazard field (Keiler et al., 2006; Bründl et al., 2009, 2015) as a tool for risk zoning in land use planning (Eckert et al., 2012, 2018) and as a facilitator for decision making including optimal design of defense structures (Bohnenblust & Troxler, 1987; Eckert et al., 2009; Favier et al., 2016).

The general concept of risk in the natural hazard field identifies hazard and vulnerability as determinants of risk (UN/ISDR, 2004). The most palpable differences in risk formulations center on the definition of vulnerability (Villagrán De León, 2006). The earliest social science definitions consider that vulnerability comprises an *internal* and *external* side, where the latter involves exposure to risk (Chambers, 1989; Watts & Bohle, 1993). Other approaches consider exposure as an important, independent factor of risk (Field et al., 2012). Natural sciences emphasize the importance of susceptibility assessment as a requirement for the set up of technical mitigation structures (Fuchs et al., 2011). Lastly, integrated approaches present vulnerability as a function of exposure, susceptibility and coping capacity (Fuchs et al., 2011; Turner et al., 2003; Weis et al., 2016). In this context, vulnerability not only depends on exposure (among other things), but it is also reinforced by human actions, such as urban development, that can alter the location of elements at risk and its resulting vulnerability.

So far, the concept of risk often does not integrate the dynamic properties of its components and the approach remains static (Fuchs et al., 2013). However, in a changing climate, the intensity and frequency of natural hazard change (Klein et al., 2014). This, coupled with changing socio-economic conditions and settlement patterns, induce shifts in risk to societies. Therefore, addressing the spatio-temporal variability of risk drivers is essential for future sustainable risk management (Fuchs et al., 2013; Peduzzi, 2019). Accordingly, avalanche risk is subject to spatio-temporal variability driven by shifts in the social and natural systems and the mechanisms underlying their interaction and dynamics (Field et al., 2012; Birkmann, 2013). Consequently, integrative approaches to risk based on knowledge transfer between social and natural sciences are now recognised as essential for addressing the complexity of risk, its drivers and inherent spatio-temporal variability (Hock et al., 2020).

The twentieth century represents a critical period, during which mountain socio-economic systems transitioned from traditional agriculture toward service-based activities following a period of rural exodus, marginalization and abandonment (MacDonald et al., 2000; Statuto et al., 2017). Accordingly, land abandonment induced the vegetation succession process from shrubs to forests (Mather et al., 1999; Bebi et al., 2009). In parallel, the transition toward service and leisure-oriented societies, especially outdoor activities (e.g. Ski tourism, trekking etc.), encouraged population and tourist influx (Barbier, 1989). This amplified the demand for accommodation and infrastructure,



mostly concentrated around tourist centers and key transportation routes (Barker, 1982). Where suitable zones for expansion are scarce, settlements were centralized in confined areas (Fuchs & Keiler, 2008). Therefore, peri-urban sprawl occurred in the vicinity of active avalanche paths, causing an increase in the damage potential resulting from snow avalanches in settlements (Keiler et al., 2005; Fuchs & Keiler, 2008). Only few studies have focused on the temporal evolution of avalanche risk driven by shifts in exposure to snow avalanche, e.g. in Davos (Switzerland), Galtür (Austria) (Fuchs et al., 2005; Keiler et al., 2005; Fuchs & Keiler, 2008) and the Sakhalin Island (Russia) (Podolskiy et al., 2014). Although, in Europe, results suggest a decrease in avalanche risk to settlements due to risk reduction measures, Keiler et al. (2005) states that avalanche risk to residential buildings increased following an increase in exposure to avalanches.

Assessing the evolution of avalanche hazard in a changing climate is crucial in order to determine shifts in future activity and the associated risk. Changes in avalanche activity and dynamics are governed by changes in snowfall, snow cover amount, properties and duration (Naaïm et al., 2013; Steinkogler et al., 2014). Spatio-temporal variability of the weather and snow characteristics (e.g. snow depth) is already documented in most European regions (Beniston et al., 2018). For example, in the French Alps (1958-2005), Durand et al. (2009) highlight marked snow depth decrease at low elevation versus less significant changes at high elevation. Also, in the Swiss-Austrian Alps (1961-2012), snow depth decreased in southern regions versus no marked change in the northeast (Schöner et al., 2019). Consequently, spatio-temporal disparities in avalanche activity are also expected. However, weather conditions and snow characteristics are not the only space-time varying factors affecting avalanche hazard. Land cover changes, mostly driven by socio-economic changes, have an impact on snow avalanches (Giacca et al., 2018; Hock et al., 2020). Indeed, vegetation cover, particularly forests, may play a crucial role in decreasing snow avalanche hazard (Salm, 1978; Viglietti et al., 2010; Teich et al., 2012) and related damages (García-Hernández et al., 2017), notably by decelerating the flow (Malanson & Butler, 1992; Anderson & McClung, 2012; Takeuchi et al., 2018).

To our knowledge, research has not yet addressed the growing need for approaches assessing simultaneous socio-environmental changes and their influence on the long term evolution of avalanche hazard, vulnerability and risk. On this basis, in this study we present an integrative procedure to analyze the evolution of avalanche risk to settlements in one prototypical avalanche prone areas of the French Alps, the upper Maurienne valley (Figure 1). Information collected from a wide corpus of supports, including historical sources, is combined with an integrative methodology associating land cover change detection using advanced image processing techniques, geohistorical investigations, and qualitative modelling of risk changes. This optimizes documentation and analysis of changes in the socio-environmental system driving the evolution of avalanche risk in all its components. We consider that avalanche risk hinges on the interaction between avalanche hazard and vulnerability of the elements at risk (Figure 2), where exposure is considered one of the drivers of vulnerability whereas sensitivity and adaption capacity are not considered. The objectives of our study are: i) to analyze the co-evolution of the socio-economic and environmental system in the upper Maurienne valley from 1860 to 2017 using a diachronic analysis of historical maps and aerial photographs. ii) Zoom into the extent of avalanche paths to examine the temporal variability of exposed settlements to snow avalanches; iii) Assess how changes in vegetation cover could have influenced the variation of hazard over time, iv) and finally, infer on the evolution of avalanche risk to settlements in the study area since 1860.

## 2. Materials and Methods

### 2.1. Study area

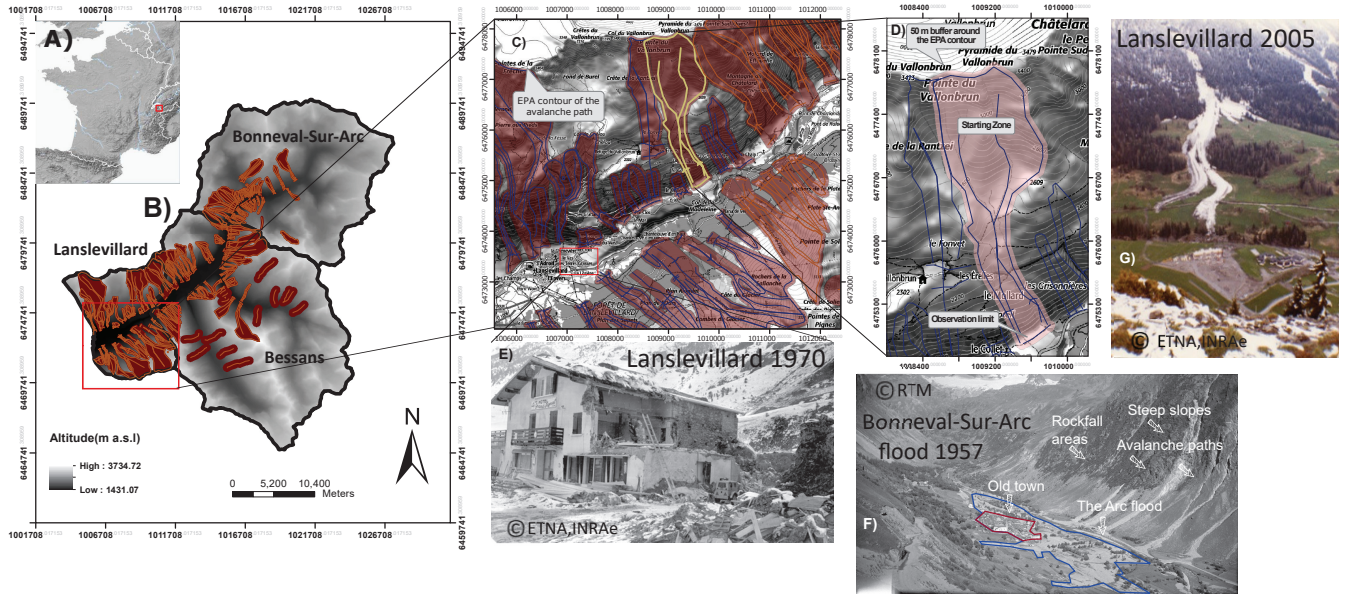


Figure 1: (A,B) Location of the study area, (C,D) Avalanche Permanent Survey (EPA) avalanche path contour and 50 m buffer around it, (E) Destroyed hotel in Lanslevillard due to the tragic 1970 avalanche (F) A view of Bonneval-Sur-Arc following the 1957 flood of the Arc river. The old city is visible in the narrow valley. It is surrounded by avalanche paths and rockfall areas located on steep slopes larger than 30°. (G) Avalanche in 2005 in Lanslevillard.

The three municipalities under study are located in the highest part of the Maurienne valley commonly referred to as the upper Maurienne (Savoy region, Northern French Alps). Bessans, Lanslevillard and Bonneval-Sur-Arc are positioned along the French-Italian borders, between 1500 and 3700 m a.s.l (Table 1, Figure 1B). The climate of the upper Maurienne is cold with relatively low mean annual precipitation ( $884 \pm 167$  mm, according to the closest station located in Bessans at 1715 m. asl) in comparison with the rest of the French Alps. Snowfall is abundant with an average of 170 days of snow between November and the end of April (Bessans meteorological station). with high altitude and steep slopes, highly promote avalanche initiation. Indeed, in the Avalanche Permanent Survey (referred to as EPA: Enquête Permanente des Avalanches (Bourova et al., 2016)), 129 avalanche paths are registered in the study area (59 in Bessans, 33 in Lanslevillard and 37 in Bonneval-Sur-Arc). In addition, more than 3000 avalanche events have been documented since 1900 (Table 1), which makes the Haute Maurienne a valuable territory for avalanche studies (Ancey et al., 2004; Eckert et al., 2008; Favier et al., 2014). The avalanche permanent survey (EPA) is the only regular and up to date avalanche monitoring system in France. Avalanche events are recorded on approximately 3900 avalanche paths in the French Alps and the Pyrenees, with quantitative and qualitative information describing avalanche characteristics e.g. deposit volume, release elevation, runout distance, type of avalanche, etc. (Bourova et al., 2016).

However, in the upper Maurienne, snow avalanches are not the sole natural hazard. Flooding, rockfalls and landslides contribute, in addition to topography, to the complexity of the area (e.g. Figure 1F shows the multiplicity of natural hazards in Bonneval-Sur-Arc). Apart from climate and topography, the socio-economic development of

the study area makes it an interesting case study. Over the last two centuries, the area went through a depopulation and agricultural decline period (Folliasson, 1916; Onde, 1942; Jail, 1977), followed by a flourishing of the tourism sector that transformed its landscape (Rambaud & Vincienne, 1964; Jail, 1973, 1977). However, the increasing demand for touristic facilities, coupled with the scarcity of suitable areas for development raises the question of the safety of settlements against natural hazards in general and snow avalanches in particular.

Table 1: Characteristics of the study area

	Whole study area	Lanslevillard	Bessans	Bonneval-sur-arc
Area( $km^2$ )	311	45	154	112
Max. elevation (m)	3735	3572	3735	3633
Min. elevation (m)	1431	1431	1655	1758
Mean elevation (m)	2630	2393	2641	2704
Number of avalanche paths in the EPA record	129	33	59	37
% Area covered by avalanche paths from the EPA	24%	53%	23%	12%
Mean elevation of EPA paths	2215	2171	2270	2205
Number of avalanche events since 1900 in the EPA record	3275	599	1358	1318

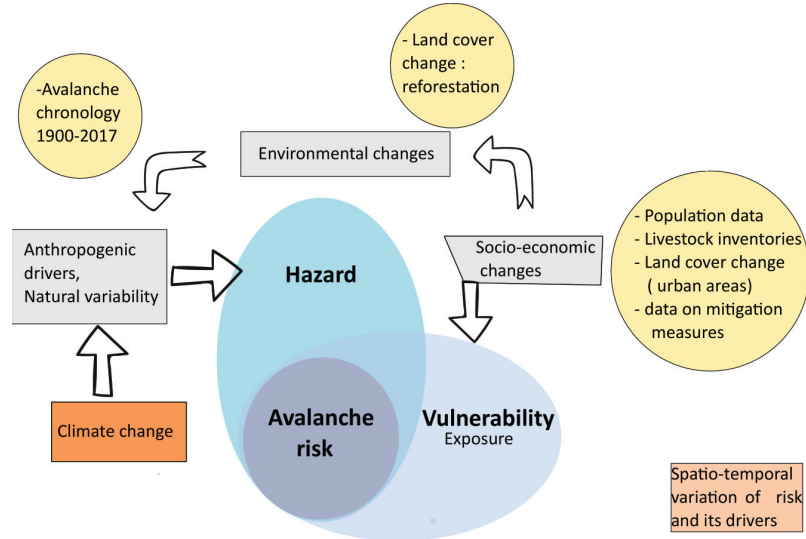


Figure 2: Co-evolution between changes in socioeconomic and environmental processes and avalanche risk as function of changes in hazard and vulnerability. Yellow circles indicate data sources used for the study.

101 A holistic interdisciplinary approach based on the cross analysis of different data sources is proposed to assess the  
 102 evolution of avalanche risk in the upper Maurienne (Figure 2). Prior to avalanche risk analysis, the co-evolution of  
 103 the socio-economic and environmental system is assessed by cross analysing various data sources. Population counts  
 104 for each of the studied municipalities (Lanslevillard, Bessans, Bonneval-Sur-Arc) were obtained from 1861 to 2015.  
 105 For the first century of the study (1861-1967), data were collected from the School of Advanced Studies in the Social  
 106 Sciences (EHESS, <http://cassini.ehess.fr>) with 5 to 20 years interval. From 1968 to 2015, data were collected from  
 107 the National Institute of Statistics and Economic Studies (INSEE), per decade (on average, 1968-2006) and every  
 108 two years for 2006-2015. Livestock inventories (1862-2013, every 20 years on average), the number of shepherds of  
 109 the entire Maurienne valley (1860-1968) and the number of cultivated areas (1862-2010, every 20 years on average)  
 110 were obtained from published data (Rambaud & Vincienne, 1964; Jail, 1969, 1977), the agricultural census published  
 111 by the Ministry of Food and Agriculture (recensement agricole), and the pastoral inquiries ("enquête pastorale",  
 112 <http://enquete-pastorale.irstea.fr>).  
 113 Land cover data from 1860 until 2017 were produced using the methodology explained in section 2.3.1. The  
 114 chronology of recorded avalanche events (EPA database) (Figure 3), the local avalanche cadaster (referred to as  
 115 CLPA: Carte de Localisation des Phénomènes d'Avalanche, (Bonnefoy et al., 2010)) and information on protection  
 116 structures were used to further identify areas at risk and infer the evolution of avalanche risk. The CLPA is the  
 117 French Avalanche map. It records the widest limits of all known avalanches that occurred in the French Alps and  
 118 Pyrenees (Bonnefoy et al., 2010). Avalanche limits are assessed with a combination of photo-interpretation and  
 119 eyewitness testimonies (Bonnefoy et al., 2010). Eventually, a qualitative model highlighting changes in land cover  
 120 and avalanche risk to settlements in the upper Maurienne was elaborated following the geohistorical methodology  
 121 proposed by Giacona et al. (2019).

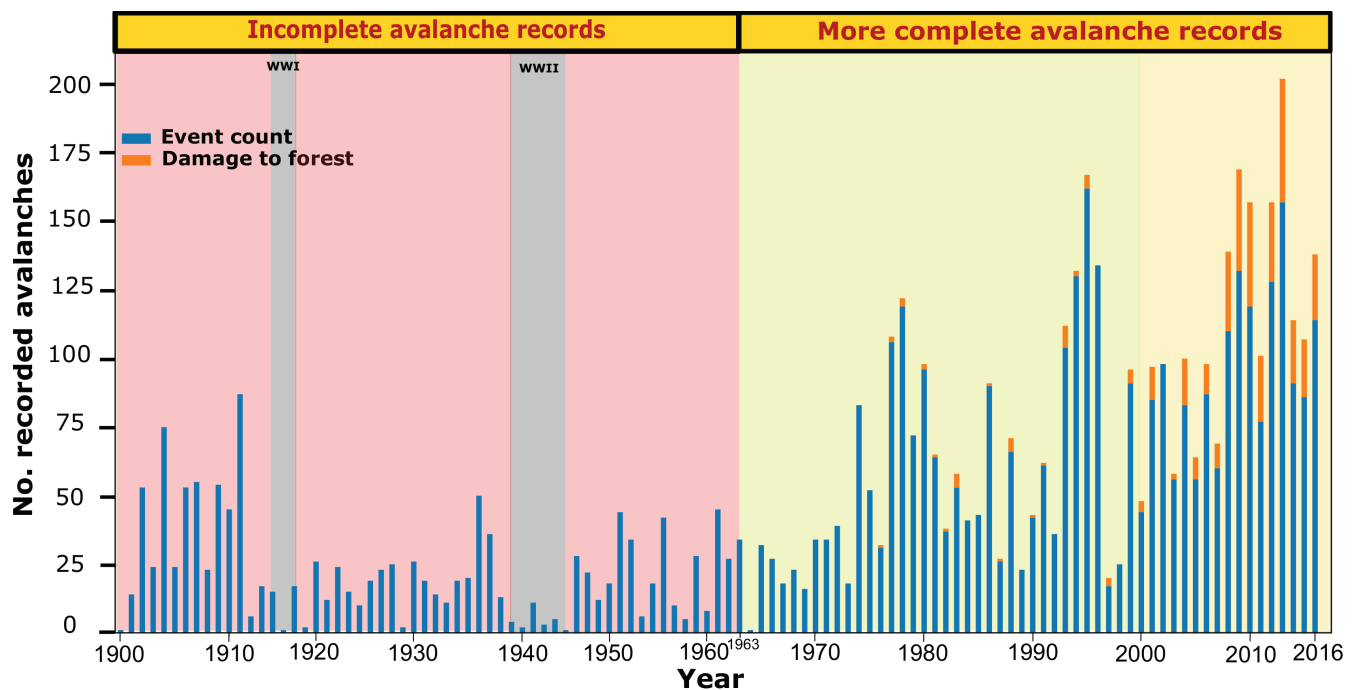


Figure 3: Chronology of avalanches reported in the upper Maurienne from 1900 to 2017 within the EPA database. Avalanches that caused forest stand disturbances are also represented. Collected data are more reliable and comprehensive following a series of reforms since 1963. Prior to that date, mainly damaging and/or large avalanches were recorded.

### 2.3. Land cover change analysis

#### 2.3.1. Historical maps: Manual digitization for land cover analysis

Historical maps were provided by the French National Geographic Institut (IGN). The maps used are the *Etat-Major* map of 1860 and the 1952 map scanned and georeferenced by IGN. Alternatively, the 1929 maps also acquired from IGN needed to be georeferenced prior to proceeding to the digitization phase. Additional information on the collected maps and their characteristics can be found in Appendix A, Table A.1.

All historical maps were manually digitized (Figure 4C). Eight land cover classes were delimited, when possible, following the old maps digitization manual proposed by Favre et al. (2013): forest, grasslands, agricultural lands, urban areas, glaciers, water bodies, main roads, rocks and sands.

#### 2.3.2. Aerial photos for land cover interpretation

Aerial photographs are a valuable, spatially complete and temporally continuous tool to analyze historical changes in land cover (Morgan et al., 2010). Therefore, three additional aerial photo collections for 1952, 1979 and 2017 were collected to provide land cover evolution from mid twentieth century until today. All the dates for the analysis are chosen based on availability and as key dates relative to agricultural decline, depopulation and world wars.

**Pre-processing:** Pre-processed aerial photos for 2017 and 1952 were obtained from IGN. The 2017 image is a true-color aerial photo while the 1952 is in black and white. For 1979, color infra-red photos were gathered in their raw form (<https://remonterletemps.ign.fr>). Prior to the photographic interpretation, raw aerial photographs needs



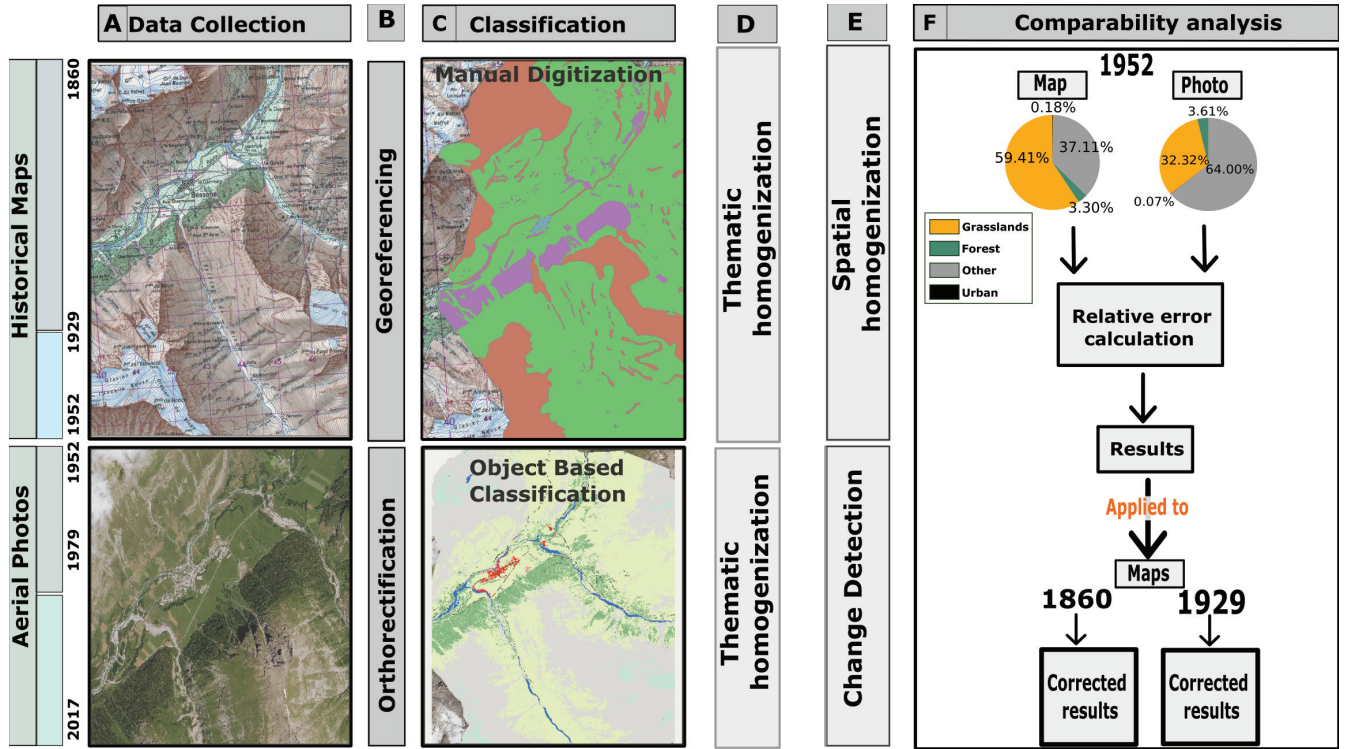


Figure 4: Methodology for land cover change analysis: (A,B) collection and preprocessing of historical maps (georeferencing) and aerial photographs (orthorectification) (C) land cover classification and (D,E,F) Change detection and comparability analysis. In (F), the pie charts represent the percent area composition of the whole upper Maurienne for the 1952 historical map (MAP) and aerial photo (Photo).

to be ortho-rectified and preprocessed (Figure 4B) to compensate the errors due to distortions and displacements (Morgan et al., 2010; Linder, 2016). In order to successfully perform an orthorectification, several additional information needs to be known. The most essential ones are the type of camera used and its characteristics such as the interior, exterior orientation and the focal length. The majority of the required information is provided in the camera calibration reports acquired from the IGN. In addition to the calibration reports, the IGN's 1 meter resolution digital elevation model (DEM) was used as the vertical reference during the ortho-rectification process. The software used to complete this task is ERDAS LPS® (Leica Photogrammetry Suite) (Intergraph, 2015). Additional information concerning the aerial photos are found in Appendix A, Table A.1.

**Object Based Classification:** Over the past years, basic pixel based classification methods were superseded by object based image analysis (OBIA) (Ma et al., 2017; Blaschke, 2001). The concept of OBIA depends upon widely used feature extraction and segmentation techniques (Blaschke, 2010) crucial for good classification results (Baatz, 2000).

The chosen technique for land cover analysis is Multiresolution segmentation (MS) offered within eCognition software that specializes in object oriented image analysis. MS is a bottom-up region based algorithm that merges two image objects based on the combination of spectral information, shape properties and a user defined scale parameter (Baatz, 2000; Darwish et al., 2003).

Accordingly, the 1979 and 2017 aerial photos were classified into seven classes : urban, forest, grasslands, rocks,

157 snow, water bodies and roads. Alternatively, the black and white 1952 image was digitized by hand. The land  
158 covers recognised are : grasslands, urban, forest and other.

### 159 *2.3.3. Data comparability and change detection analysis*

160 The result of all the steps described before is two series of land cover maps. The first one is produced from the  
161 digitization of historical maps and the second series is generated from the analysis of aerial photographs.

162 As previously mentioned in other studies, leveling thematic and spatial details prior to combining and comparing  
163 heterogeneous data is necessary to reduce errors on change-detection caused by map inconsistencies (Petit & Lambin,  
164 2001, 2002; Falcucci et al., 2007; Pelorosso et al., 2009). For this purpose, the technique proposed by Petit & Lambin  
165 (2001) for integration by pairs of successive maps was used to conduct the change detection analysis.

166 First a thematic generalization (Figure 4D) is applied to the 5 land cover maps. Original land cover categories  
167 were merged into four classes: urban, forest, grasslands and other. Since the difference in the aerial photographs  
168 resolution is relatively minor, the change detection analysis is directly analyzed from the thematically homogenized  
169 maps. However, for the historical maps, a spatial homogenization is required before proceeding to the change  
170 detection phase (Petit & Lambin, 2001).

171 To spatially homogenize the layers digitized from the historical maps, the map with the coarser resolution of each  
172 successive pair is selected as the target map while the other map is transformed from vector form to a 1 meter  
173 resolution raster. Thereafter, it is spatially aggregated from 2 up to 20 meter using the majority rule for the  
174 aggregation procedure. This step is essential in order to compensate for scale dependency problems of landscape  
175 patterns (Turner et al., 1989; Wu, 2004; Falcucci et al., 2007).

176 Next, landscape metrics were computed in order to detect the resolution that present the highest landscape similarity  
177 between the target and the generalized data. Five landscape metrics ( the landscape shape index, Shannon's diversity  
178 index, the mean patch fractal dimension, the total core area index and the Total edge contrast index) are sufficient  
179 to explain more than 80% of the variability in the landscape pattern (Riitters et al., 1995; Petit & Lambin, 2001,  
180 2002). These metrics were calculated using Fragstats4.2. The normalized euclidean distance was then computed  
181 and the resolution with the smallest distance between the metrics was selected as the optimal resolution.

182 Performing a historical reconstruction of land cover change is a challenging task since it often involves comparing  
183 maps derived from different sources. For some applications, the data integration method provided consistent results  
184 when maps of different sources were used (Petit & Lambin, 2002). However, in our case, the analysis failed to  
185 detect the proper transition of the urban areas between 1929 (historical map) and 1952 (aerial photos). Change  
186 detection showed a decrease in the urban area, that is inconsistent with the real urban evolution in the zone. Thus  
187 having 1952 as a pivot year common to both the maps and aerial photos series ensures the continuity of change  
188 analysis results and translates the dynamics of land cover evolution from 1860 until 2017. However, this does not  
189 ensure the proper comparison between the landscape composition matrices derived from the historical maps and  
190 aerial photographs. Hence, the 1952 pivot year can be used to quantify the bias resulting from the maps and, once  
191 assessed, to have a complete homogenized series of comparable landscape matrices.

192 To calculate the bias (Figure 4F), let 1952 be the pivot year, common to both aerial photographs and historical  
193 maps. First let  $S_k$  be the surface area corresponding to land cover type k.

$$S_k = P_k \times S_0, \quad (1)$$

where  $S_0$  is the total surface of the study area and  $P_k$  is the fraction of land cover type k. Knowing that  $\sum P_k = 1$  and  $\sum S_k = S_0$  we can calculate the relative error  $\varepsilon_k$  per land cover class using the 1952 aerial photography as reference as follows:

$$\varepsilon_k = \frac{S_0 P_{km} - S_0 P_{kp}}{S_0 P_{kp}} = \frac{P_{km} - P_{kp}}{P_{kp}}, \quad (2)$$

leading

$$P_{kp} = \frac{P_{km}}{\varepsilon_k + 1}, \quad (3)$$

where  $P_{km}$  is the fraction of k resulting from the 1952 historical map and  $P_{kp}$  is the fraction of k recorded from the analysis of the 1952 aerial photos.

Since all the land cover data, generated from historical maps, were already homogenized to a comparable resolution following the methodology suggested by Petit & Lambin (2001), we can assume that the relative error derived for the pivot year applies to the previous years. Thus we can create virtual matrices that represent the landscape composition as if it was analyzed from aerial photographs.

Let  $S_{kp}'$  be the virtual area corresponding to land cover type k knowing that only the area digitized from the map is available :

$$S_{kp}' = \frac{P_{km}}{\varepsilon_k + 1} \times S_0. \quad (4)$$

Thus,  $P_{kp}'$ , that represents the potential fraction of land cover k as if it was generated from an aerial photos, is :

$$P_{kp}' = \frac{S_{kp}'}{\sum S_{kp}'} = \frac{S_0 \frac{P_{km}}{\varepsilon_k + 1}}{\sum S_0 \frac{P_{km}}{\varepsilon_k + 1}} = \frac{\frac{P_{km}}{\varepsilon_k + 1}}{\sum \frac{P_{km}}{\varepsilon_k + 1}}. \quad (5)$$

#### 2.3.4. Land cover change analysis in avalanche paths

To asses land cover change in avalanche prone areas, a 50 m buffer was created around the contour of the 129 avalanche paths from the EPA database within the study area. Then, change detection analysis was applied within this newly created buffer following the methodology explained above. Mean evolutions within avalanche-prone terrain were then computed for further analysis.



### 3. Results

#### 3.1. Evolution of land cover, population and livestock in the upper Maurienne

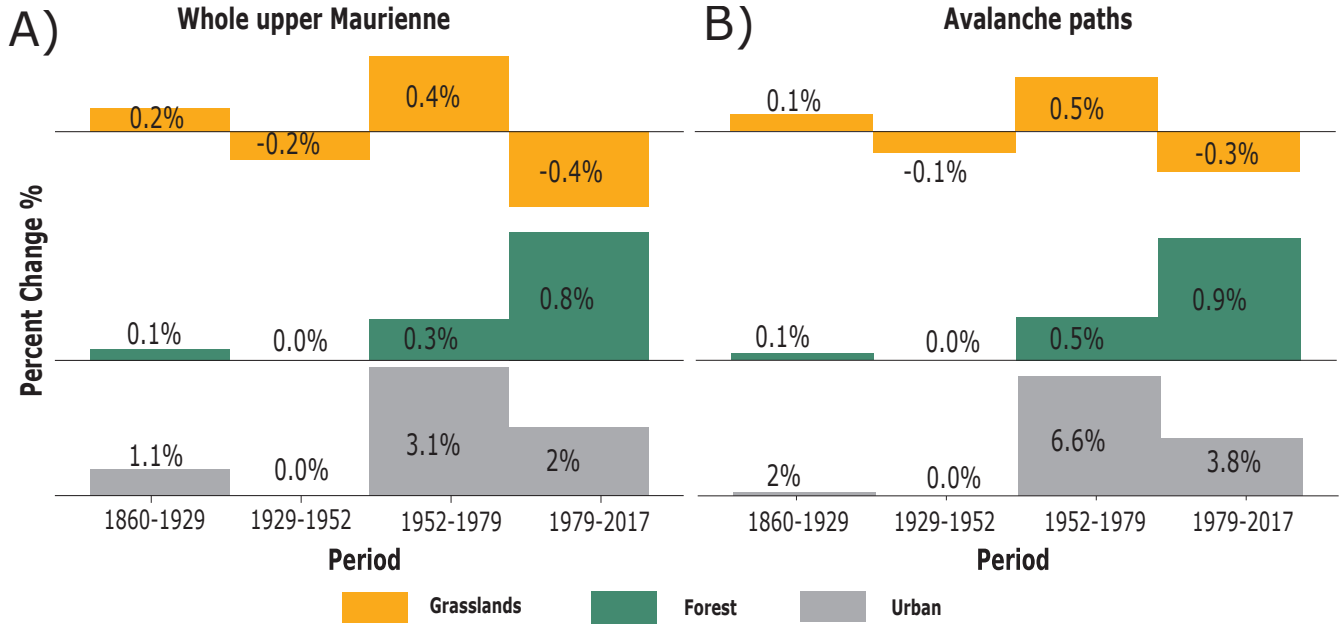


Figure 5: (A) Yearly land cover changes in the whole upper Maurienne (values rounded to the nearest tenth) (B) Yearly land cover changes within the extension of all avalanche paths from the EPA record (values rounded to the nearest tenth).

By applying the methodology suggested above, we were able to trace the co-evolution of land cover, population and livestock in the upper Maurienne valley as function of five sub-periods: 1860-1929, 1929-1952, 1952-1979 and 1979-2017. Overall, land cover trends shows that the study area is mostly covered by grasslands zones that fluctuate with time. On the other hand, forested areas show an increasing trend in terms of percentage total area. They hit the 5% coverage mark in 2017 after being stuck in the 3% zone for more than a century. Urban areas remain the least dominant landcover, never surpassing 0.25% of the area, but with a significant increasing trend over the study period (Figure 6).

Between 1860 and 1929, grasslands area increased by 14% (0.2%/year) whereas forests were very slowly stabilizing and expanding (0.1%/year) (Figure 6, Figure 5A). Cross analysis of the population and agro-pastoral data shows that, from 1861 until 1926, while population declined by 35%, 33% and 38% in Lanslevillard, Bonneval-Sur-Arc and Bessans, respectively, the number of breeders (1860-1914), cattle and sheep (1861-1923) also declined by 38%, 43% and 84%, respectively (Figure 10). In addition, around 70 to 80% of cultured areas vanished between 1862 and 1930 (Figure 10). In addition, during this period, the urban area increased by 56% (1.1%/year) (Figure 6, Figure 5A).

For the second period (1929-1952), analysis shows a 5% decline in the grassland areas (Figure 5A). The decline coincides with an intensification of the depopulation (additional 30% loss by 1954) and a further decline of the number of breeders (50% decline since 1914) and cattle (additional 9 % loss since 1929) (Figure 10). A stagnation in the establishment of the forests and development of urban areas is also observed (Figure 6, Figure 5A).

In the second half of the twentieth century, the rate at which the population was declining slowed down, especially in Lanslevillard and Bonneval-Sur-arc (Figure 10). Between 1952 and 1979, grasslands increased by

233 11.2% (Figure 6, Figure 5A). Forest growth rate also increased (0.3% yearly increase) and urbanization surged  
234 (87% increase 1952-1979) (Figure 5A). The maximum yearly urban growth of 3.5% was recorded during this period  
235 (Figure 5).

236 After the increase in 1952-1979, grasslands decreased by 15.6% between 1979 and 2017 (Figure 5). The major  
237 decline in pastoral areas was accompanied by a fast reforestation process (31% increase from 1979 to 2017) (Figure 5).  
238 Shortly after 1979, depopulation halted. The population in the entire area increased by almost 50% (1975-2017)  
239 (Figure 10) which coincides with an expansion of the urban areas (78%) (Figure 6, Figure 5A).

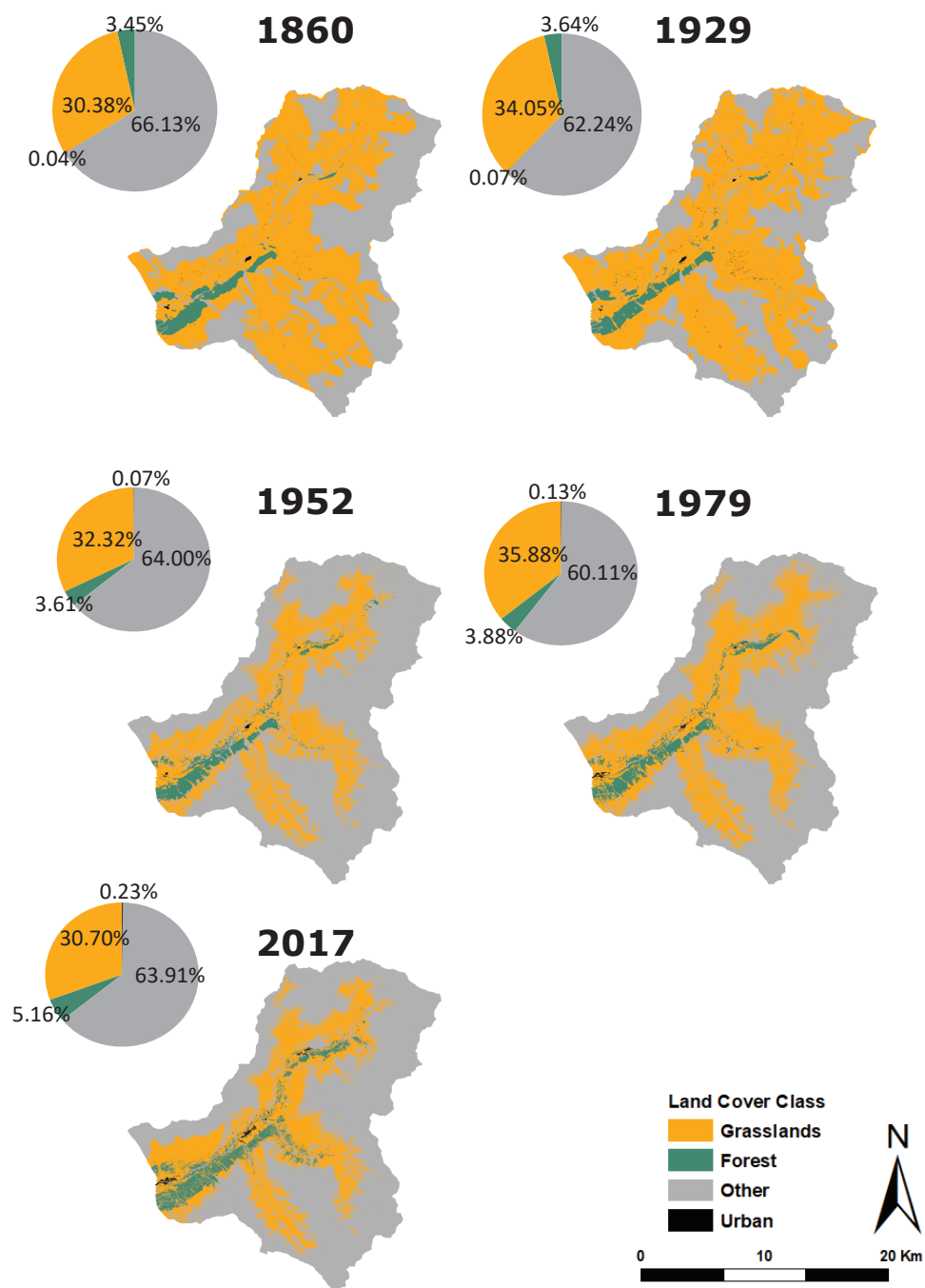


Figure 6: Diachronic land cover analysis of the upper Maurienne between 1860 and 2017. Pie charts represent the percent area composition of the whole upper Maurienne for each land cover map.

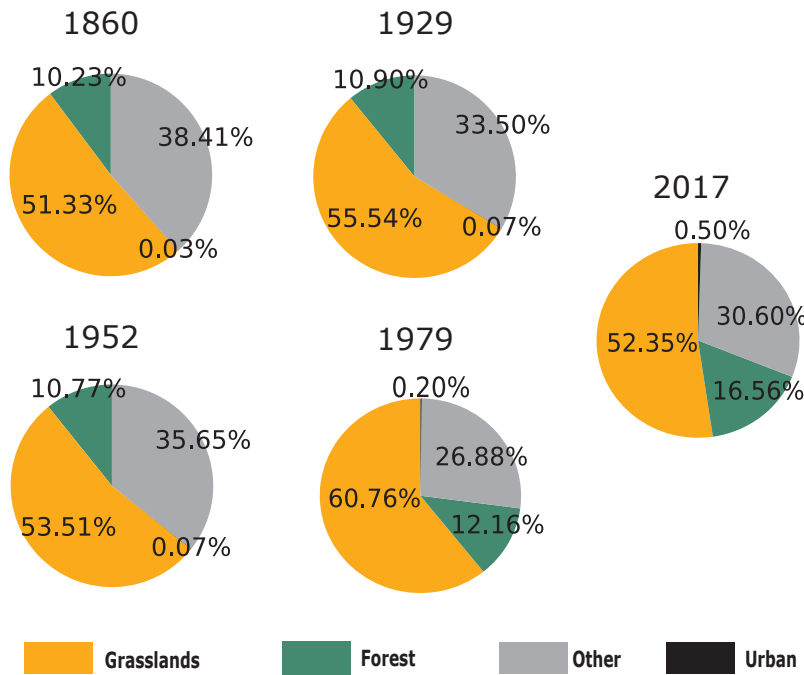


Figure 7: Percent area composition within the extension of avalanche paths from the EPA record in the Upper Maurienne from 1860 until 2017.

### 3.2. Evolution of land cover in avalanche paths

#### 3.2.1. Evolution of settlements exposed to avalanches

In 2017, urbanization covered on average 0.5% of the areas (Figure 7). Between 1952 and 1979, urban areas increased by 6.6% per year in the vicinity of avalanche paths in the upper Maurienne (Figure 5B), and by 3.8% per year from 1979 to 2017. This phenomena is particularly observed in Lanslevillard and Bonneval-Sur-Arc.

Figure 8, shows the evolution of the urban area within the extent of the deadliest avalanche that ever hit Lanslevillard. In February 1970, the Northern Alps were hit by a heavy snowfall wave during which it continuously snowed for ten to twenty days (Jail, 1970). Heavy snowfall, combined with abnormally low temperatures and a considerable accumulation of snow staged the perfect situation for disastrous avalanches formation. On February 24, 1970, an avalanche deviated from its usual path (*La Combe de Pisselerand* EPA 5 track into *couloir du Pichet*) to hit the newly constructed urban area of Lanslevillard. That day, eight people died, ten were injured and five buildings were destroyed (Jail, 1970; Ancy, 2009). The majority of buildings affected in 1970 did not exist in 1952 (Figure 8). So, already, the urban transition during this period increased the exposure of the newly constructed urban area that was left unprotected despite that a similar avalanche took the same exceptional path a century ago (Jail, 1970). Therefore, in 1972, four snow deflection structures were installed to protect the affected area (Figure 8). Two structures were positioned at 2430 and 2410 m a.s.l. at the *Plan de la Cha* (PPR, 2004). Their main role was to restrict the deviation of avalanches initiating in *La Combe de Pisselerand* to avoid a repeat of this exceptional avalanche.

Fifty years later, the urban area within the avalanche extent continues to grow and reaches a maximum in 2017



260 (Figure 8). Nowadays, EPA sites 5 and 205 where the avalanche occurred are labeled as highly sensitive inhabited  
 261 zones. The fact that the 1970 avalanche was never seen again doesn't reduce the vulnerability of the expanded  
 262 urban area. In fact, the same area is also affected by the *Rocher Roux* avalanche that initiates below 2300 a.s.l.  
 263 on the same *Pichet* track (EPA 3) (PPR, 2004). Contrary to the *Pisselerand* one, this avalanche is very frequent  
 264 and occurred 15 times between 1902 and 1966. However, until today, the two other deviation structures located  
 265 upstream of the village grant a good level of protection against it.

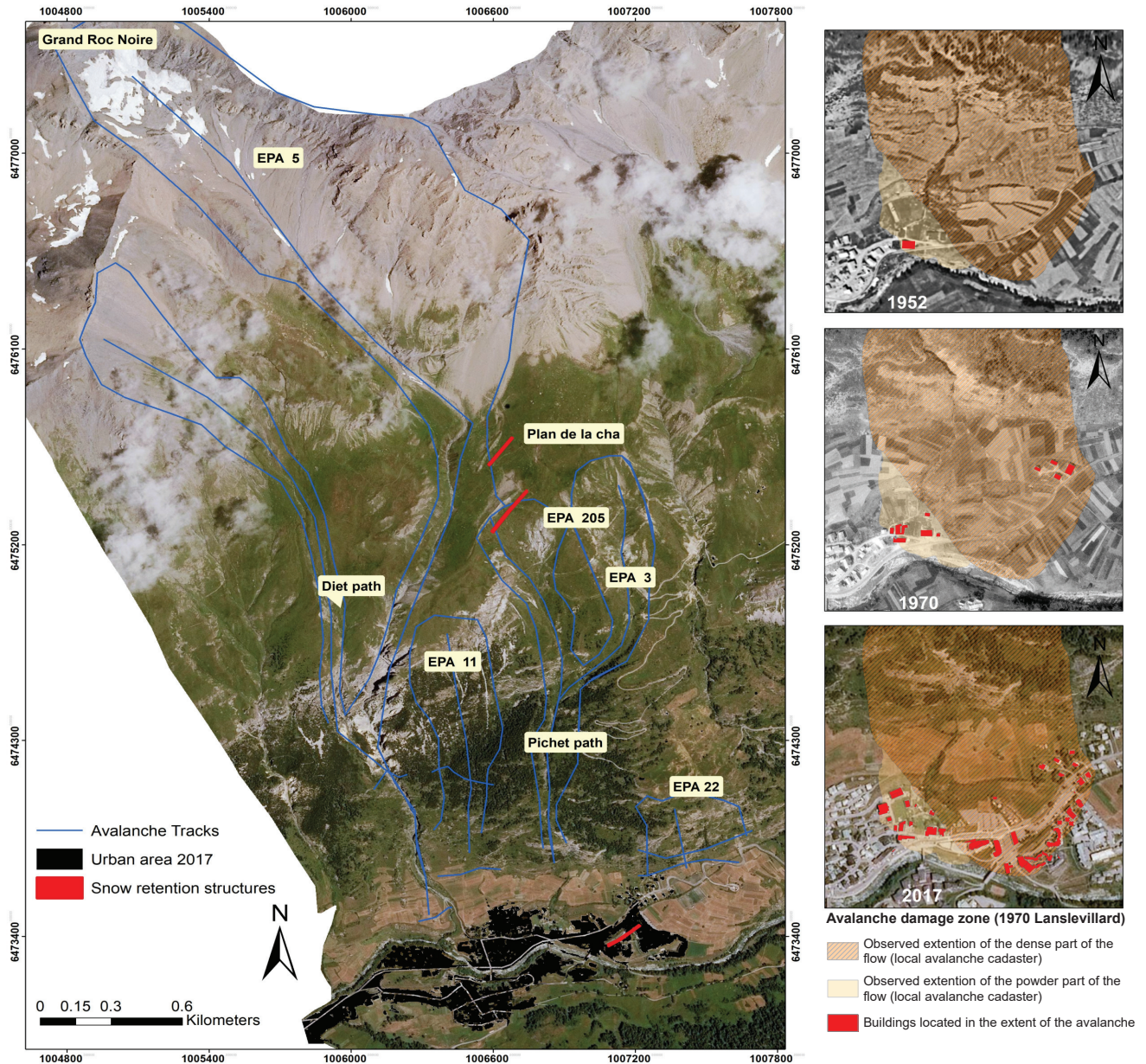


Figure 8: Left: location of snow deflection structures within the paths concerned by the major avalanche of 1970 in Lanslevillard. Right: extent of the 1970 avalanche in Lanslevillard and evolution of the urban area at risk (red) from 1952 to 2017.

Another example is Bonneval-Sur-Arc. The village is located in the narrow upper part of the valley. Therefore,



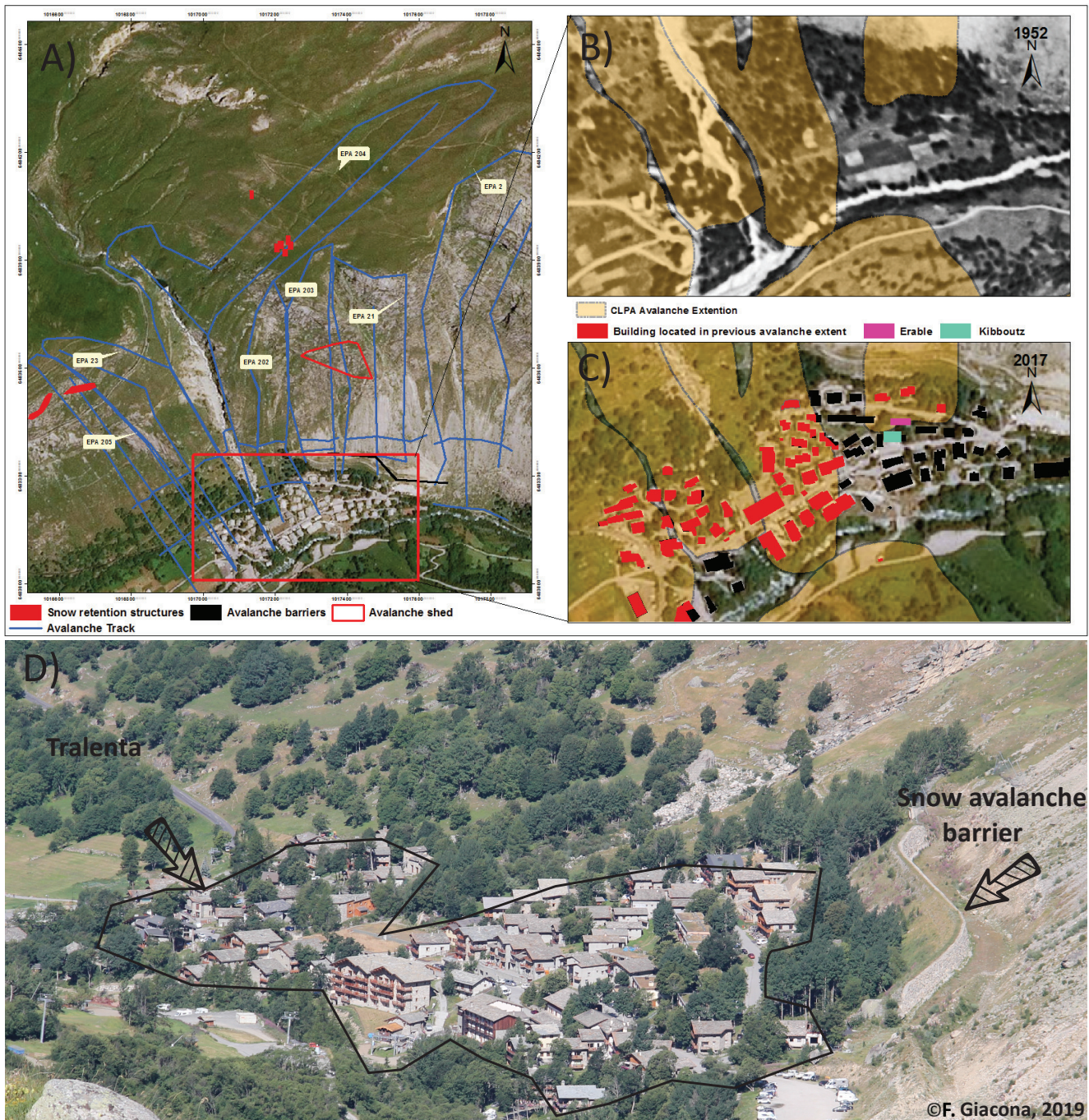


Figure 9: The Tralenta district in Bonneval-Sur-Arc: (A) aerial photography of Tralenta surrounded by avalanche paths and their numbers according to the EPA database, (B) the situation of the urban area in 1952, (C) the complete development of Tralenta in 2017 and (D) a picture of the study area taken in 2019 showing the protective barricade.

an urban expansion was a must to accommodate the increasing touristic demand. The Tralenta district, east of the old city, is the last inhabited place (farthest) in the upper Maurienne. The development of the Tralenta in late 1960's (Megerle, 2018), coincides with the opening of the ski resort and flourishing of tourism in the area. The newly constructed accommodations were mostly owned by locals and offered exclusively to tourists (Megerle, 2018). The Tralenta is directly affected by *Tralenta*, *Merlon*, *Gabions* and *Clappier Faudon* pathways that were respectively

273 subjected to a 14.33%, 2.54%, 8.5% and 0.75% increase of their urban area between 1952 and 2017 (Table 2). Today,  
274 the urban areas below the aforementioned avalanche paths in the Tralenta district are classified as highly sensitive  
275 inhabited zones, namely zone where avalanche risk to settlements is high.

276 According to a witness, prior to the establishment of Tralenta, an avalanche usually passed at the location of *Kibboutz*  
277 and *Erable* chalets (CLPA no.31694) (Figure 9). However, in general, no deadly avalanche have ever occurred in  
278 these paths. However, the lack of victims or severe damage does not necessarily alleviate the vulnerability of the  
279 exposed urban area. In fact, with the construction of the Tralenta, the local vulnerability largely increased and, as  
280 a result, protective barricades against avalanches were built in the *Merlon* Zone (Figure 9) in 1972 (PPR, 2011).  
281 After that, the urban envelope continued to expand until late 1980's. To alleviate the increasing vulnerability and  
282 to insure additional protection of the heavily populated area, the barricade built in 1972 was shifted upward in 2011  
283 (PPR, 2011).

Table 2: List of most affected paths by the urban expansion in Bonneval-Sur-Arc (1952-2017).

District	Path Name	EPA Path Number	CLPA <sup>1</sup> Number	% change in urban area <sup>2</sup>	Avalanche Events <sup>3</sup>
Tralenta	<i>Clappier Faudon</i>	21	7	+0.8%	9
	<i>Gabions</i>	23	11	+8.5%	7
	<i>Tralenta</i>	202	9	+14.3%	None
	<i>Merlon</i>	203	8	+2.5%	None
	<i>La Lenta</i>	204	10	+2.8%	None
	<i>L'Oratoire</i>	205	12	+4.7%	None
Old City	<i>Druges</i>	25	14	+2%	9

<sup>1</sup> *Carte de Localisation des Phénomènes d'Avalanche (avalanche cadaster).*

<sup>2</sup> *Change as a percentage of area within the extension of each path.*

<sup>3</sup> *Recorded between 1952 and 2017 in the EPA.*

284 *3.2.2. Evolution of forest cover within avalanche paths*

285 Figure 5B and Figure 7 show continuous forest increase in avalanche paths over the study period, from 10.2%  
286 in 1860 to 16.6% in 2017. Before 1952, reforestation rates were slow ( $<0.1\%$  /year) (Figure 5B). However, after  
287 1952, reforestation rates sped up ( $0.5\%$ /year) and by 1979 the forest area in avalanche paths increased by 14%.  
288 Thereafter, the forest continued to expand at a more rapid pace ( $0.93\%$ /year) and by 2017 it increased by an  
289 additional 36% (Figure 5B).



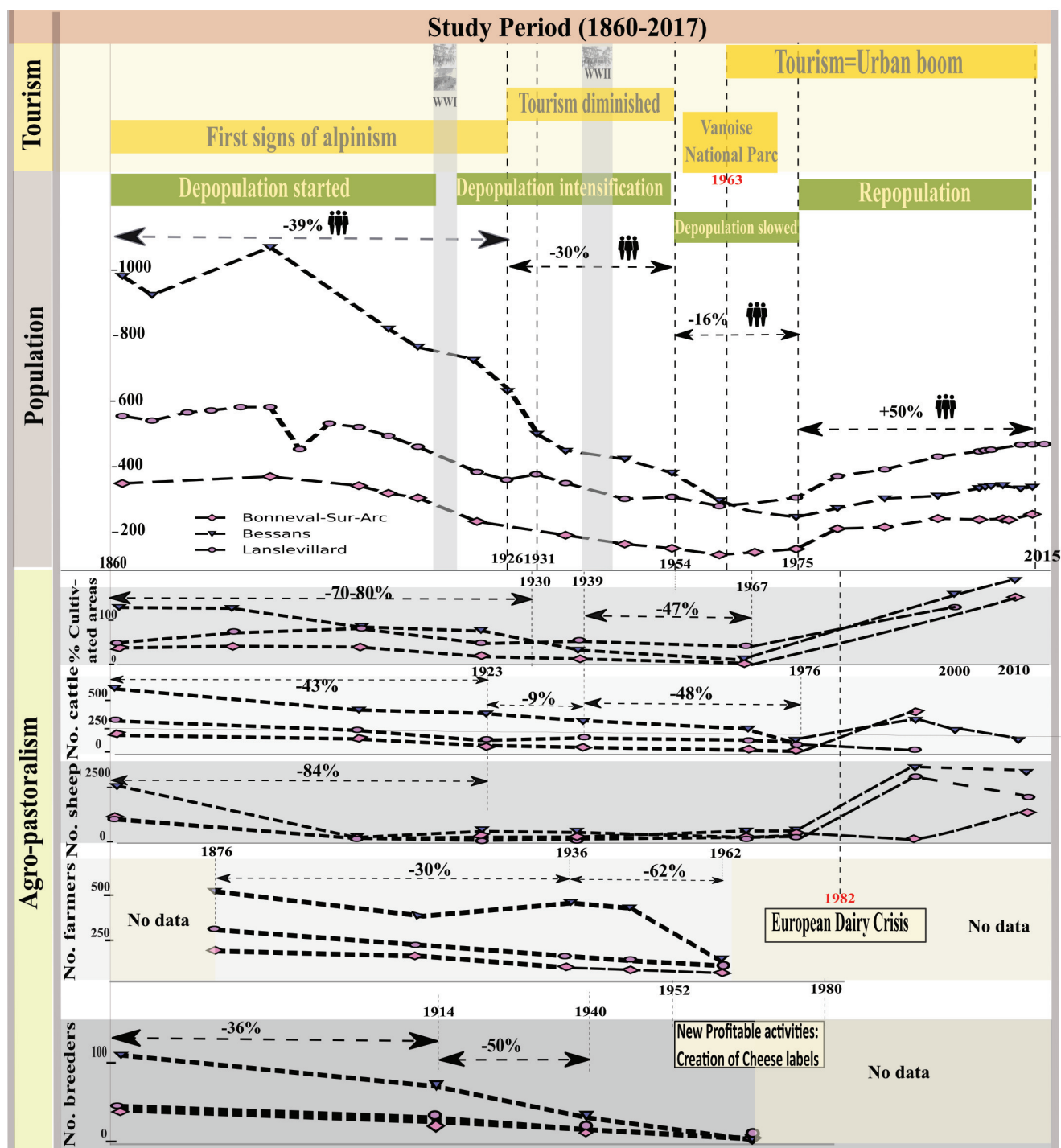


Figure 10: Diachronic evolution of the socio-environmental context in the upper Maurienne from 1860 until 2017. Qualitative data highlighting the evolution of tourism are deduced from Jail (1977) and discussed, when needed, in the discussion.

## 4. Discussion

### 4.1. Diachronic analysis of land cover

Two series of historical maps and aerial photos were used to assess the evolution of land cover in the upper Maurienne valley. As for other of such studies, our analysis is subject to a range of uncertainties. Most common uncertainties associated with land cover analysis stems from the classification and change detection phase. Thus, to reduce the errors associated with both, we adopted the methodology suggested by Petit & Lambin (2001) that facilitate change detection analysis through the homogenization of spatial and thematic information across data sources. The methodology was applied to layers digitized from historical maps. Three types of errors are recognized when performing thematic and spatial equalization.

First, aggregation errors caused by the aggregation from small to a broader level. Aggregation errors are also associated with the change from vector coverage to raster coverage. We checked that these errors were negligible and less than 1% for all land cover types in all the years (Appendix B, table B.1).

The second type of errors is related to the thematic aggregation of the different maps. In this study, the thematic aggregation errors were not included in the analysis since, before the classification phase, the different land cover were identified and grouped into similar categories.

No explicit measure of the error associated with the classification is performed due to the absence of ground truth data. However, by reducing the number of classes to the four most relevant land-cover types, it was possible to cut down the potential occurrence of misclassification errors.

The comparison of the land cover composition between the 1952 map and aerial photos shows several discrepancies especially in the grasslands, other and urban class that were over-represented in the historical maps (appendix C, Figure C.1). The higher representation of grasslands in the map is related directly to the under representation of rocks. Small patches of rocks dispersed among the grasslands in higher altitude were most probably only represented as grasslands on the maps. This discrepancy propagates also to older maps. As for the urban areas, the difference is mostly due to cartographic generalization techniques (mostly scale variation). Finally, it is important to note that maps represent a simplification of a much complex reality. Thus, a large part of the uncertainty stems from the different sematic models used to create the map and its intended use.

Comparability between landscape matrices generated from aerial photography and historical maps remained an issue. Thus, for the pivot year (1952), the relative error was calculated (Appendix C: table C.1) and applied to correct the maps and, thus, create new matrices that potentially represent the state of land cover as if they were analyzed from aerial photos. This innovative method helps create one complete series of comparable landscape matrices. However, overall, the procedure did not modify the trajectory of the evolution. A comparison between the rate of changes analyzed before the correction (appendix C: Figure C.2) and after (Figure 5) shows the coherence of the results.

Finally, the 50 m buffer zone around avalanche paths is also a source of spatial error. The 50 m extension beyond the current limits of avalanche paths in local avalanche cadaster and chronicles was made as a pragmatic compromise between: i) including all potential avalanche prone terrain (current extensions are regularly exceeded), and ii) not exaggerating the number of exposed elements.

#### 327 4.2. *Evolution of the socio-environmental context in the upper Maurienne*

328 We assessed the co-evolution of the socio-economic and environmental system in the upper Maurienne valley as  
329 function of five sub-periods: 1860-1929, 1929-1952, 1952-1979 and 1979-2017. These changes could be successfully  
330 linked with the evolution of population and social practices.

##### 331 4.2.1. *1860-1929: Start of the depopulation phase*

332 Mountains have long been considered as migration territories (Fontaine, 2005). The decrease in population,  
333 number of breeders, livestock and cultivated areas, between 1860 and 1929, clearly implies the start of the de-  
334 population and land abandonment phase (Onde, 1942; Rambaud & Vincienne, 1964; Jail, 1969, 1977). Although  
335 depopulation and abandonment are the main reason that explains the decreasing population trend (Jail, 1977), the  
336 First World War (1914-1918) and its subsequent impact on the society also indirectly contributed to the population  
337 loss. Indeed, according to Gex (1922) the deaths during the First World War in our study areas accounted for 5%  
338 of the population in 1911 (1566 in Bessans, Lanslevillard and Bonneval-Sur-Arc). Still, since no sharp population  
339 decline is observed during the war period (1914-1918) (Figure 10), it is very likely that the subsequent impacts of  
340 war, e.g. decrease in birth rates linked to postponed marriages, displaced and fragmented families, also contributed,  
341 in addition to the abandonment, to depopulation. This has been confirmed for different departments in France e.g.  
342 Savoy department (France) (Gex, 1922) and Hérault department (France) (Raynal, 1946).

343 This period also marks the start of the transition from deforestation to reforestation in the entire Maurienne  
344 valley (Battipaglia et al., 2014) and in France in general (Mather et al., 1999; Kauppi et al., 2006). The reforesta-  
345 tion observed between 1860 and 1929 is attributed to the combination of factors that helped reduce pressures and  
346 restore forests e.g. depopulation (Mather et al., 1999), forest policies (Brugnot, 2002) and agricultural intensifi-  
347 cation (Mather & Needle, 1998). Indeed, as areas in high altitudes were abandoned (Mather et al., 1999), forest  
348 encroachment in the study area occurred mostly between 1800 and 2350 m.asl (Appendix E, Figure E.1). The  
349 intensification of grazing on sowed grasslands at lower elevations (Mather & Needle, 1998) explains the increase in  
350 grasslands observed between 1860 and 1929.

351 During this period, except agro-pastoralism, all three villages had little to no activity (Jail, 1977). So they all  
352 slowly turned towards tourism as a second source of income. The first signs of touristic activity appeared at the end  
353 of the nineteenth century with alpinism in Bessans and Bonneval-Sur-Arc Jail (1969, 1977). The different touristic  
354 activities during this period led to the construction of several hostels to accommodate the tourists (Jail, 1973), that  
355 might have modestly contributed to the urban expansion during this period.

##### 356 4.2.2. *1929-1952: Population and agricultural decline*

357 Overall, the 1929-1952 period marks a stagnation in the development of the area due to the combined effect of  
358 abandonment, depopulation and wars.

359 The combined decline in grasslands, livestock and breeders is potentially a delayed consequence of the agricultural  
360 abandonment that began during the previous period. However, this should have encouraged a faster reforestation  
361 between 1929 and 1952. Hence, the observed delay in forest regeneration is potentially associated with a rise in  
362 transient livestock reported by Jail (1969) between 1928 and 1964.

During the Second World War tourism completely stopped in some areas, such as Bessans, contributing to population decline in the area (Jail, 1977). Likely, the effect of the war on the overall development of the area is somewhat reflected in the stagnation of urban development, especially since Bessans and Lanslevillard were completely destroyed during the Second World War (Millere, 1997). This caused a housing crisis (Millere, 1997) due to the combined effect of building destruction and the economic recession that occurred in the interwar period (Loiseau et al., 2005).

#### 4.2.3. 1952-1979: Major urbanization of the valley

Between 1952 and 1979, grasslands increased. One possible explanation is the shift toward more profitable activities such as the creation of high value cheese label (Chauchard et al., 2010). This, in addition to the implementation, in 1962, of the European Common Agricultural Policy (CAP), encouraged intensive cattle farming and pastoral activities. The aim of this new policy was to encourage agricultural productivity via modernization of farms to achieve food self-sufficiency in Europe, and France in particular (Ackrill, 2000).

Another important finding was the peak in urbanization. This is likely to be related to tourism. Indeed, during this period, the tourism sector started to redevelop (Jail, 1973). The presence of the Vanoise national park in 1963 played a role in boosting summer tourism, and heavily contributed to a much needed economical boost in the area (Mauz, 2007). The impact of tourism can be seen in the increase in the number of available beds for tourists from 250 (before the second war, (Pairaudeau, 1983)) to 2890 in 1978 (Marnezy, 1979). In addition, complete districts were exclusively built and reserved for tourism. For example, the Tralenta area developed in the 1960's, and exclusively reserved for touristic and secondary accommodations (Megerle, 2018). In 1978, the district alone held 27% (786 beds) of the available beds in the upper Maurienne (Pairaudeau, 1983).

#### 4.2.4. 1979-2017: Major Reforestation and Urbanization driven by a surge in tourism

The small push in grasslands during the previous period (1952-1979) lasted until the European dairy crisis in 1983 (Chauchard et al., 2010). Thereafter, the pastoral lands returned rapidly to their previously declining trends. As a result, forest encroachment sped up.

The combined impact of repopulation and tourism contributed to the increase in urban areas between 1979 and 2017. This is reflected in the rise of primary residences (1975-2016) (INSEE, 2016), secondary residence (Megerle, 2018) and the number of beds available for tourists (30% increase, 1978-2017) (INSEE, 2017). Similarly, Roca (2013) highlight a tripling of mountain vacation properties in France between 1968 and 2008.

#### 4.3. Evolution of avalanche hazard

Land cover changes in avalanche paths are a direct result of socio-economic changes that occurred in the study area between 1860 and 2017. These changes can impact avalanche activity (García-Hernández et al., 2017; Giacona et al., 2018), especially forests which are valued for their avalanche protection services (García-Hernández et al., 2017). Their primary role is to stabilize the snow in release areas, thus preventing initiation of snow avalanches (Salm, 1978). However, in the upper Maurienne, only 2 out of 129 avalanche paths (1 in Bessans and the other in Lanslevillard) are forested up to their release area. Therefore, the forest, despite the major reforestation that occurred, is not able to provide protection by preventing snow avalanche release. However, this trend is not specific

to our study area since the majority of the release areas in alpine environments are located above the treeline (Giacona et al., 2018).

Mountain forests have also the capacity to decelerate flowing avalanches (Malanson & Butler, 1992; Anderson & McClung, 2012). However, identifying if the reforestation process in the upper Maurienne plays a role in slowing down avalanches without explicit modeling of the physical processes is challenging (Zgheib et al., 2019). According to Bartelt & Stöckli (2001), forests lose their protective capacity once they are destroyed by large avalanches initiating above the timberline. Since 1976, 380 events that damaged the forest are recorded in the study area (Figure 3). In line with the ideas of Bartelt & Stöckli (2001), it can be concluded that reforestation in the upper Maurienne have no power against large flowing avalanches. However, we acknowledge that there are considerable discussions among researchers with respect to the capacity of forests to decelerate avalanches : while scientists generally believe that destroyed forest can't decelerate large avalanches, others showed that this may be possible in some circumstances (Takeuchi et al., 2018).

A direct analysis of the evolution of avalanche occurrence numbers using historical data of recorded avalanches (Figure 3) introduces bias related to sources and does not reflect the natural evolution of avalanche activity (Giacona et al., 2017). As a result, the increasing trend observed in the upper Maurienne from 1900 to 2017 (Figure 3) mostly reflects that the record is much more comprehensive over the recent decades. Therefore, in order to objectively show the evolution of avalanche hazard in the upper Maurienne, we mostly refer to studies made on the French Alps where, using advanced statistical methods, researchers were able to depict evolution trends in avalanche occurrence. Indeed, in addition to land cover, changes in avalanche activity are also governed by modification in snow and weather variables (Naaim et al., 2013). While snow cover at low elevations has generally declined, at high elevations changes are either insignificant or unknown (Hock et al., 2020). In addition, Eckert et al. (2010c) showed that, overall, climate change had little impact on avalanche occurrence numbers in the Northern French Alps from 1948 to 2005, in good agreement with other studies by Laternser & Schneebeli (2002) and Schneebeli et al. (1997) in Switzerland. Eventually, Lavigne et al. (2015) showed that the overall stagnation in the French Alps results from combined decrease in avalanche occurrence numbers at low elevations due to scarcer snow conditions versus potential increase of avalanche occurrence numbers at high elevations areas such as upper Maurienne. In summary, the impact of climate change on avalanches in high mountains, like the upper Maurienne, is most likely a change in the magnitude and nature of events (Eckert et al., 2010a, 2013; Corona et al., 2013; Pielmeier et al., 2013; Naaim et al., 2016; Hock et al., 2020). This, combined with the lack of protection provided by the reforestation against avalanche initiation and propagation, in the upper Maurienne, suggest that avalanche hazard in the study area was and still is very high with no clear decreasing trend.

#### 4.4. Evolution of avalanche risk in the upper Maurienne

The temporal evolution of avalanche risk depends on the change of hazard and vulnerability in which we include exposure. These changes are driven by shifts in the socio-economic and natural systems of the upper Maurienne valley since 1860. As avalanche activity in the upper Maurienne was arguably more or less steady for the entire period, the evolution of avalanche risk primarily depends on changes in the vulnerability of the elements at risk (Figure 11). Since 1952, the number of buildings exposed to snow avalanches has been increasing due to the

development of tourism e.g. Tralenta district in Bonneval-Sur-Arc (section 3.2.1,4.2.3). With the growing number of tourists, tourism-related businesses bloomed, increasing the attractiveness of the area and leading to its consequent re-population (Figure 10). This result ties well with previous studies wherein increase of exposure of buildings to avalanches was observed in the European Alps (Fuchs et al., 2005; Keiler et al., 2006; Fuchs & Keiler, 2008). Similarly, Hock et al. (2020) assess with high confidence that over the recent decades people and infrastructures, in high mountains, became more exposed to cryospheric hazards such as snow avalanches.

Changes in vulnerability can also occur due to the presence of technical risk reduction measures (Fuchs et al., 2017). The aforementioned results (section 3.2.1) shows that in Lanslevillard and Bonneval-Sur-Arc barricades and deflection structures were indeed built in 1972 to protect the urban area. However, mitigation structures cannot decrease exposure to the point where risk is non-existent. This is important to acknowledge because if mitigation methods were infallible, extreme winters such as 1998/1999 wouldn't have been so fatal for the European Alps (Gruber & Margreth, 2001; Rousselot et al., 2010). As examples, we mention i) the Tacconnaz avalanche in 1999 (Chamonix) that broke through all the barriers installed and destroyed a part of the forest and few houses located below (Rapin & Ancey, 2000); ii) the Montroc avalanche (1999, Chamonix) that left comparable damages to the horrific winter of 1970 in Val-D'isère (Rapin & Ancey, 2000) and Lanslevillard; iii) the 1999 Evolène avalanche in Switzerland (Wilhelm et al., 2000). Hence, despite the presence of technical risk reduction structures in our study area, their effectiveness cannot be entirely guaranteed on the long term. For this reason, the presence of technical mitigation measures is not considered in zoning plans in France. Indeed, DGPR (2015) in general prohibits the construction in highly hazardous areas even if protection structures are installed. Only if several criteria are met, such as the lack of available space for development outside of risk areas, construction is permitted (DGPR, 2015). This seems to be the case of Bonneval-Sur-Arc where, due to the low availability of suitable land for development, areas like Tralenta have developed even if they are surrounded by avalanche paths.

Therefore, avalanche risk in the upper Maurienne arguably increased between 1860 and 2017, mostly due to a concentration of settlements in the vicinity of avalanche paths. Thus, more people are exposed, making them more vulnerable to snow avalanches. One might argue that being exposed does not imply vulnerability to natural hazards (Field et al., 2012). However, as Birkmann (2006) explains, although vulnerability controls the degree of loss of a given element, exposure controls the number of elements that can potentially be affected, so that focusing on exposure may be sufficient to catch the first-order trend in risk evolution which is highlighted in our qualitative diachronic model (Figure 11). Also, one may argue that our interpretation of risk evolution is valid only if avalanche activity in the study area was constant. Under this assumption, risk changes depend on the evolution of vulnerability including the change in exposure driven by socio-economic and environmental factors. We gave arguments to justify why a more or less steady avalanche hazard may be realistic for our case-study. However, further work could clearly refine our results. These would imply fully quantitative risk assessment, including quantitative probabilistic-numerical avalanche modelling (Eckert et al., 2010b), analysis of the vulnerability in all its dimensions (physical, social, economic, etc.) and dynamic evolutions induced by changes in environmental and socio-economic drivers (Farvacque et al., 2019). This would allow designing successful disaster risk reduction strategies (Fuchs et al., 2019).

Eventually, in the context of our currently changing climate, future projections predict an increase in wet snow



474 avalanche activity (Castebrunet et al., 2014; Hock et al., 2020). This, coupled with an expected increase in exposure  
475 and the possibility that current risk reduction approaches become increasingly ineffective ( mitigation structures,  
476 warning systems, etc.) to climate change (Hock et al., 2020), imply further potential increase in avalanche risk in  
477 high mountains of the world. Thus, expansion of our work to future conditions would be beneficial, as a contribution  
478 to the elaboration of effective adaptation strategies.

#### 479 *4.5. Wider relevance of the results obtained*

480 Even if we have never attempted to extrapolate our data outside the study area, we are convinced that similar  
481 results could have been obtained for many high alpine valleys. The upper Maurienne has indeed been chosen as  
482 an archetypal case-study, so that overall trends in socio-environmental conditions and avalanche risk are arguably  
483 more or less similar. Notably, socio-economic and environmental patterns associated with land abandonment and  
484 depopulation are common to the majority of Alps, e.g. in Italy (Velli et al., 2018), Switzerland (Gellrich et al., 2007)  
485 and other European mountains e.g. Pyrenees (Mottet et al., 2006), Cantabrian mountains (Spain) (García-Llamas  
486 et al., 2018). Also, climate warming affects the whole mountain environment in a similar drastic way.

487 However, patterns of change may vary locally depending on socio-economic and/or environmental peculiarities.  
488 Exposure of local communities to avalanche risk may vary regionally (Hock et al., 2020), and depend on the  
489 historical development of the settlements under study (Fuchs et al., 2004). For instance, exposure highly depends  
490 on the combination of the size of tourism industry, infrastructure development and availability of suitable areas  
491 for expansion. In turn, development is regulated by urban planning strategies and laws that also vary from one  
492 place to another. Also, factors affecting snow avalanche occurrence such as altitude, slope, climate, the location  
493 and number of avalanche paths etc., vary locally. As an illustration of this spatial variability, in our study area,  
494 most of the reforestation took place in Lanslevillard due to more favorable condition (altitude, climate) and the  
495 existence of a larger forest cover in 1860 facilitating forest recovery. Similarly, urban expansion was the largest in  
496 Lanslevillard due to the closeness to the largest ski resort in Val Cenis. However, it is in Bonneval-Sur-Arc that  
497 the highest number of buildings exposed to avalanches exist mostly due to the lack of space for development and  
498 the large number of active avalanche paths (Refer to Appendix D for an overview of land cover change in each of  
499 three municipalities: Bessans, Lanslevillard and Bonneval-Sur-Arc). All in all, even if the case study choice and our  
500 extensive methodology should be seen as guarantees of the robustness of the conclusions reached, the work should be  
501 reproduced in other contexts to generalise our results and, hence, refine our understanding of the profound ongoing  
502 changes affecting mountain socio-environmental systems.

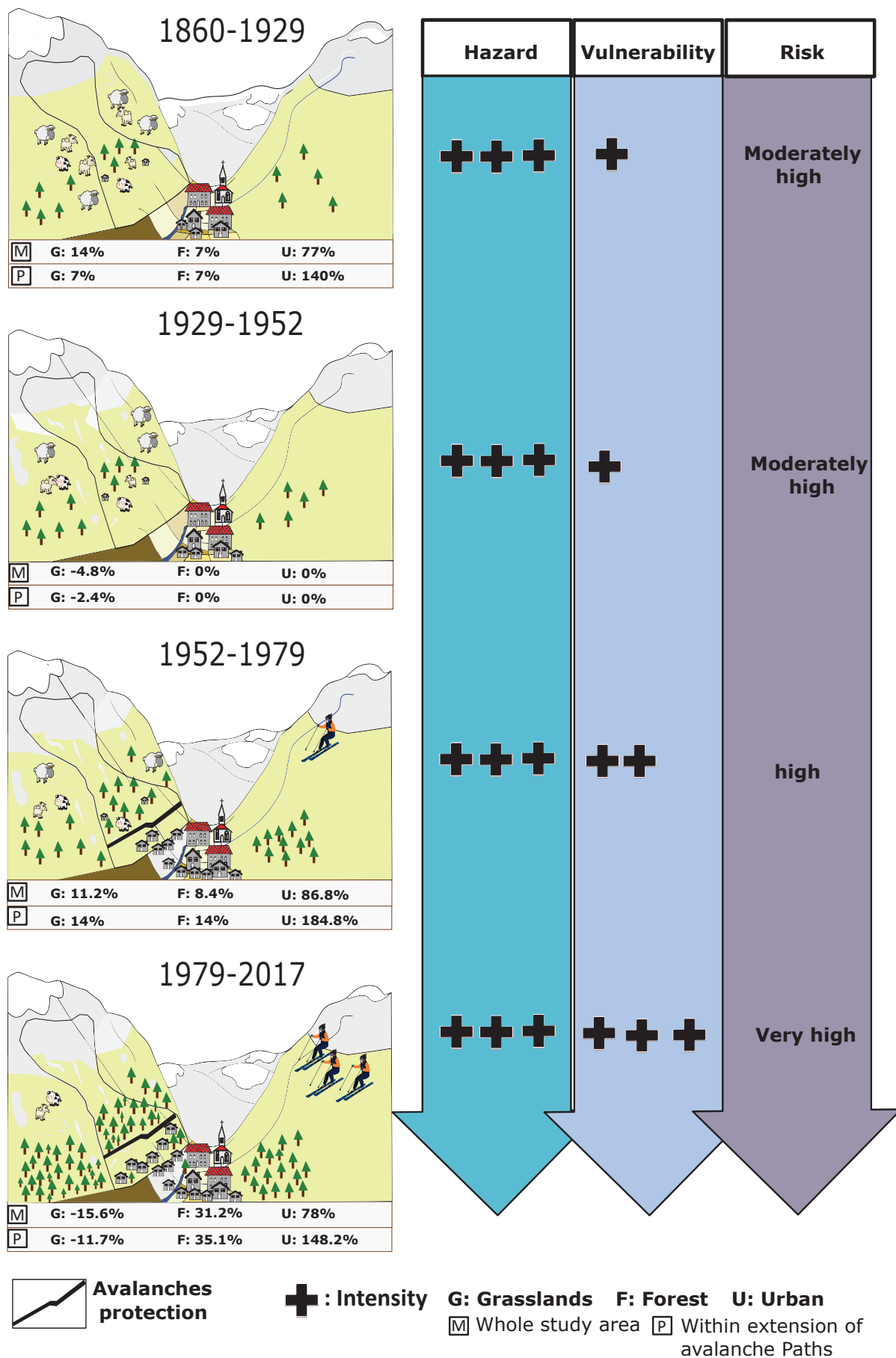


Figure 11: Co-evolution of land cover, avalanche risk and its components from 1860 to 2017 in the upper Maurienne valley. For each of the four sub-periods, this qualitative model sums-up changes in land-cover and in the different components of avalanche risk to settlements.



## 5. Conclusion

By combining a large corpus of sources including historical maps, aerial photographs, population and livestock inventories with advanced processing techniques, we assessed the co-evolution of land cover and the socio-economic system in the upper Maurienne from 1860 to 2017. First, different land cover classes were identified and digitized. Then, the land cover maps stemming from the historical map series were spatially and thematically homogenized to enhance their inter-comparability. Finally, a bias correction was used to create one complete series of comparable landscape matrices using 1952 as the common correction year. Using the same approach, the evolution of land cover in avalanche paths was also assessed, allowing inference of the evolution of avalanche risk to settlements. Ultimately, a qualitative model highlighting changes in land cover and avalanche risk to settlements in the upper Maurienne was elaborated.

The 1860-1929 period marks the start of the rural depopulation that intensified between 1929 and 1952. As a result, agricultural lands were slowly abandoned and pastoral activities reduced. The impact of abandonment is mostly visible in the 1929-1952 period, with the decrease in grasslands and in the number of cattle and sheep in the area. After 1952, winter and summer tourism grew and new touristic accommodations were established in the upper valley to host the incoming visitors. Most of the newly constructed areas were built in the vicinity of avalanche paths, increasing their exposure and consequent vulnerability to snow avalanches. Reforestation was also a result of agricultural abandonment. It began in 1860 and sped up mid twentieth century. However, reforestation of avalanche paths remains incomplete with still almost no forests in avalanche release zones. This, coupled with the complexity of forest-avalanche interactions, indicate that a drastic hazard reduction compensating vulnerability increase is unlikely. Hence, despite the technical protection measures installed by the local authorities in the 1970's, avalanche risk in the study area increased locally, due to an increase in the vulnerability of exposed settlements.

In the future, scientists predict an increase in risks due to natural hazards in high mountain areas. As illustrated with our work, spatio-temporal evolution of risk depends not only on changes in hazard, and may even be mostly driven by the evolution of vulnerability in all its dimensions. Thus, integrative assessment techniques that mobilizes the knowledge and expertise of various biophysical and social disciplines are mandatory to elaborate efficient mitigation strategies. To this aim, our approach could be transferred with benefit to other areas and natural hazards.

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Table A.1: Characteristics of the maps and aerial photographs used to document the evolution of land cover in the study area.

	Year	Name	Scale/resolution	Source
Historical maps	1860	Etat Major	1/40000	IGN
	1927	Lanslebourg	1/50000	IGN,EPA
	1929	Tignes	1/50000	IGN,EPA
	1952	Lanslebourg	1/50000	IGN
	1952(partially updated)	Tignes	1/50000	IGN
Aerial photos	1952	-	0.5m	IGN
	1979	-	1.5m	IGN
	2017	-	1.5m	IGN

Table B.1: Spacial aggregation errors associated with the transformation from vector to raster formats.

Land cover class	1860	1929	1952 (map)
Grasslands	0.00%	0.00%	0.00%
Forest	0.00%	-0.01%	0.00%
Urban	-0.02%	0.05%	-0.92%
Other	0.00%	0.00%	0.00%
Average	-0.01%	0.01%	-0.23%

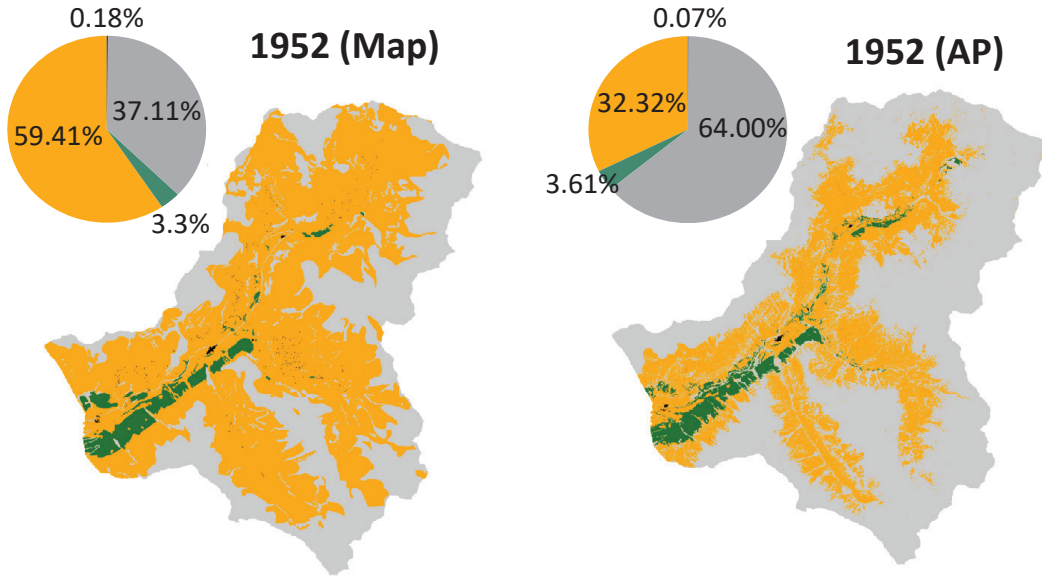


Figure C.1: 1952 Land cover digitized from the historical map (MAP) and analyzed from aerial photography (AP).

Table C.1: Relative error per land cover class  $\varepsilon_k$  in absolute value calculated using the 1952 aerial photography as reference for the entire study area and within the extension of EPA avalanche paths.

	Forest	Grasslands	Urban	Other
Relative error (entire area)	-0.08	0.83	1.78	-0.42
Relative error (within EPA avalanche path)	-0.07	0.33	3.00	-0.48

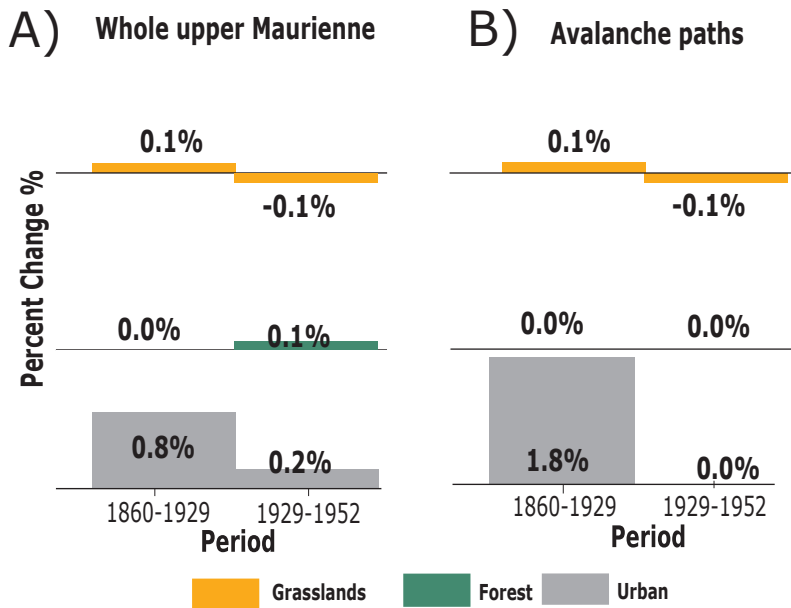


Figure C.2: Yearly land cover changes for the first two periods obtained by direct comparison of the homogenized maps prior to correction: A) for the entire study area B) within the extension of EPA avalanche paths.

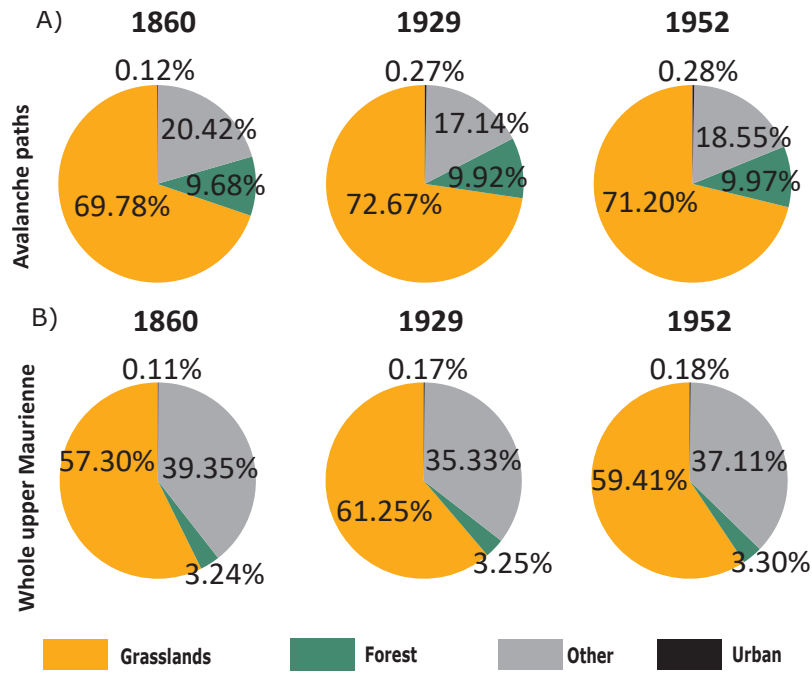


Figure C.3: Land cover composition results obtained from the digitization of historical maps and prior to correction: A) within the extension of EPA avalanche paths, B) for the entire study area.

#### Appendix D. Highlights of land cover evolution for the three municipalities of the upper Maurienne

First we notice a continuous increase in forested areas for the three municipalities and within the extension of their avalanche paths, but with some local disparities. Overall, forest is most abundant in Lanslevillard followed by Bessans and Bonneval-Sur-Arc. The lower elevation of Lanslevillard creates a more favorable situation for reforestation in general. This, coupled with the fact that initially (in 1860) Lanslevillard was covered by more forests than the other municipalities, explains why Lanslevillard has the highest percentage of forests in 2017 (Figure D.1,D.2).

Similarly, Lanslevillard is the municipality with the highest percentage of settlements (Figure D.1). However, according the extension of avalanche paths, settlements in Bonneval-Sur-Arc are more exposed to snow avalanche (Figure D.2). Bonneval-Sur-Arc is located in the narrowest part of the Maurienne valley. The Low availability of suitable areas for development combined with the high touristic demand for accommodations explains this large number of settlements in the vicinity of avalanche paths. The significant increase over the last part of the study period corresponds to the Tralenta area.

The evolution of grasslands is less homogeneous. We notice at first that after 1952 grasslands show a decreasing trend in the three municipalities (Figure D.1). The pattern is more complex when we try to compare 1860 with 1952 especially in Lanslevillard. Pie charts show an increase from 26.43% to 41.10% in Lanslevillard from 1860 and 1952 (Figure D.1,B). This increase is most probably an error inherited from the adjustment methodology used. Clearly, the creation of a comparable matrix was impossible for Lanslevillard. The same problem is found also when concentrating on the areas within the extension of avalanche paths (Figure D.2,B). In these, we notice an increase in grasslands after 1952. It is possible that some bare lands (classified as rocks) were colonized by grass species in



862 2017 thus explaining the slight increase in grasslands. Overall, what we can conclude is:

- 863 1. Forest fraction increased in the three municipalities, mostly as a result of the retraction of pastoral activities  
864 highlighted by the decrease in cattle, sheep and spearheads (Figure 10).
- 865 2. Urban settlements expanded, sometimes close to avalanche prone areas. This is mostly associated with the  
866 lack of suitable areas available to build and the increasing touristic pressure .
- 867 3. Most of the exposed buildings are located in the Tralenta area in Bonneval-Sur-Arc.
- 868 4. The majority of the forest is located in Lanslevillard and Bessans.

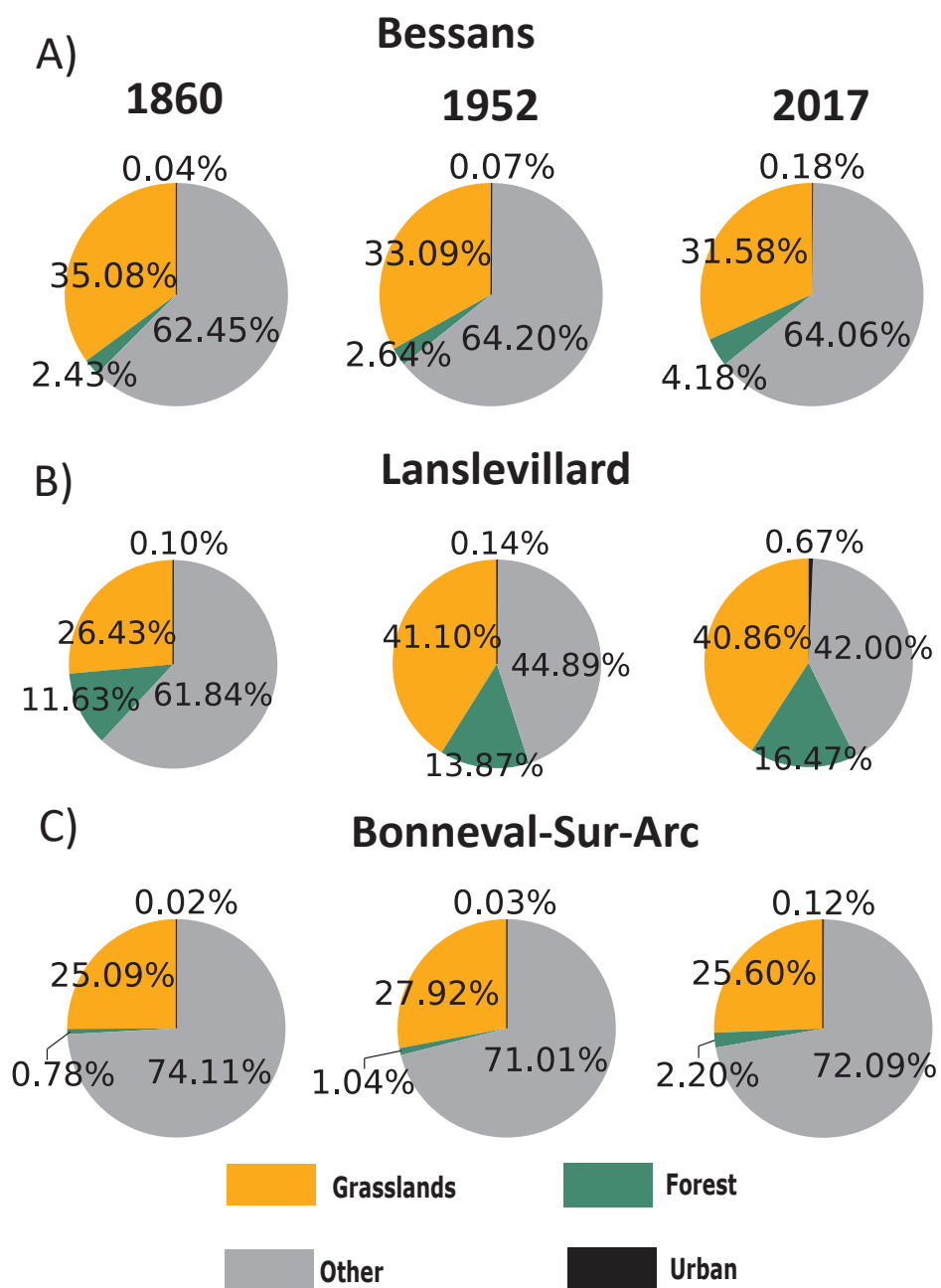


Figure D.1: Land cover composition from 1860 to 2017 for A) Bessans B) Lanslevillard C) Bonneval-Sur-Arc.

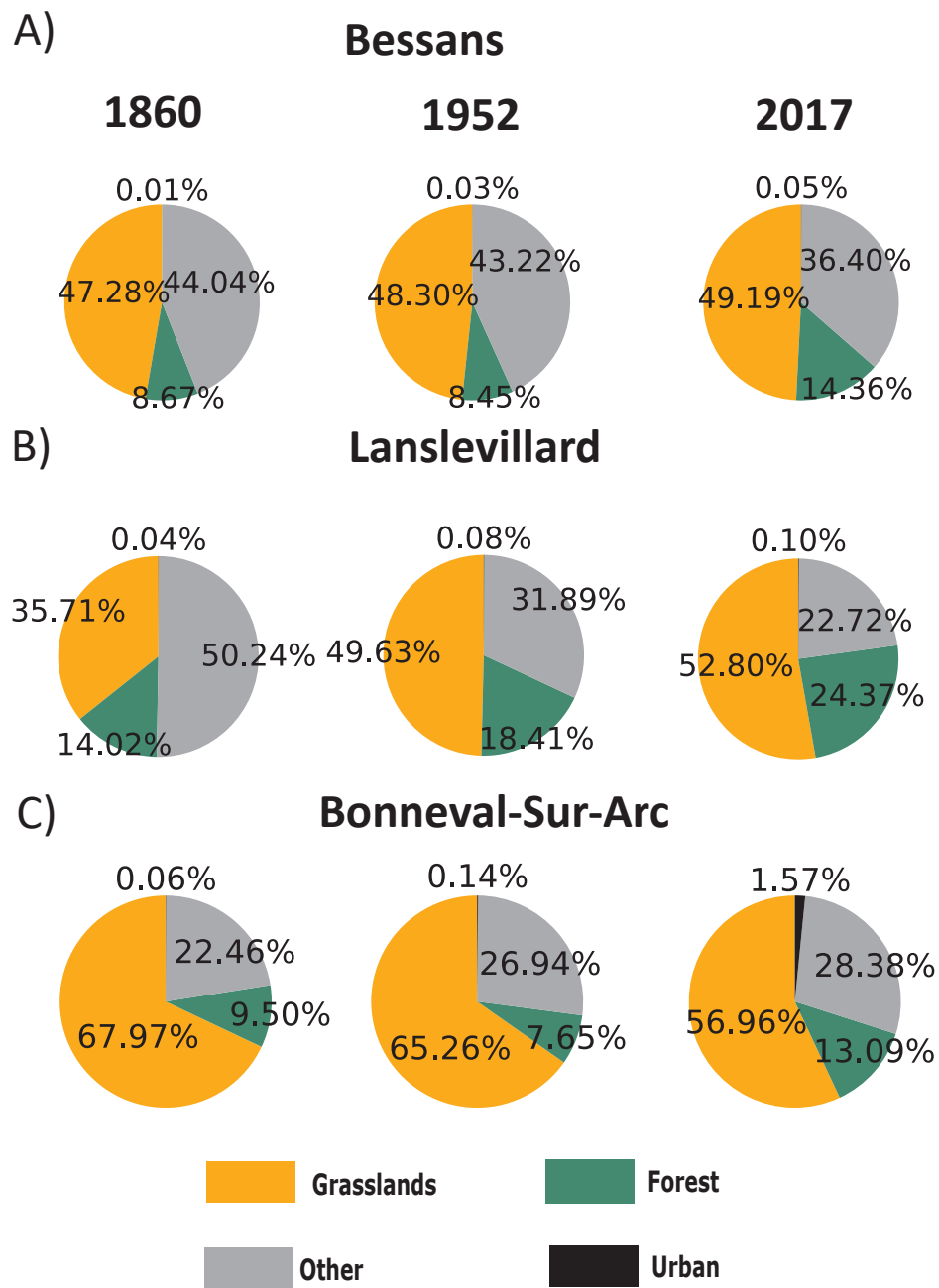


Figure D.2: Land cover composition within the extension of EPA avalanche paths from 1860 to 2017 for A) Bessans B) Lanslevillard C) Bonneval-Sur-Arc.

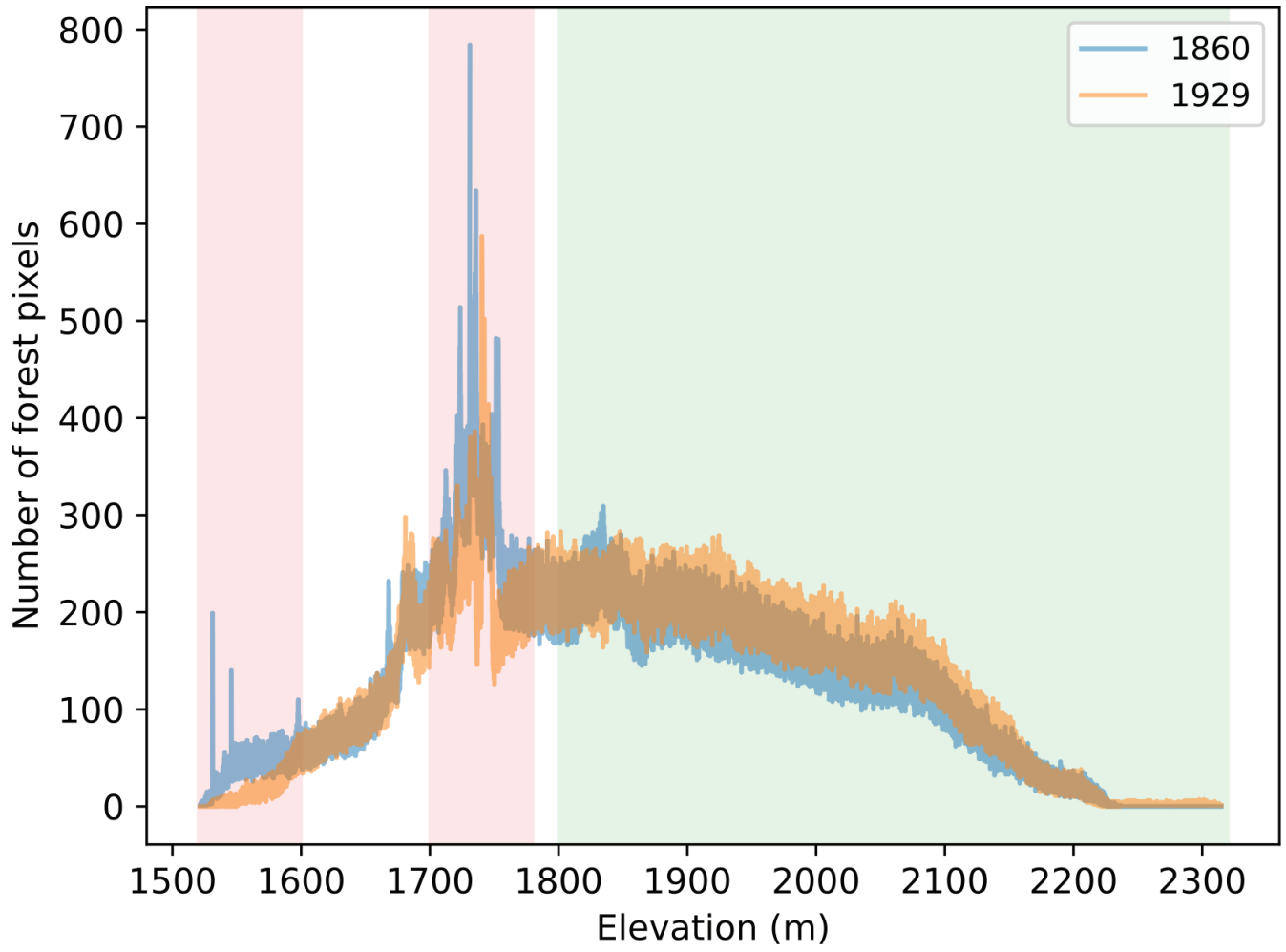


Figure E.1: Attitudinal distribution of the forest pixels in 1860 and 1929. The zones highlighted in 'red' represent attitudinal zones where forest cover decreased from 1860 to 1929. Zones in 'green': altitude where forest cover increased (1860-1929).