Tree rings as ecological indicator of geomorphic activity in geoheritage studies

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Abstract

Mountain areas are characterized by geomorphic processes, especially mass wasting and avalanches, which may impact the landscape affecting also the biological component, trees included. If sites colonized by trees are characterized by geomorphic features with a high *Global* and *Scientific Value*, including *Representativeness of geomorphological processes*, *Educational Exemplarity*, and *Integrity*, they can be considered geomorphosites. In the framework of assessment of the *Scientific Value* of geomorphosites, *Ecological Support Role* is of great importance. Hence, tree rings derived information can be used as indicators to refine the *Scientific Value* of the sites and also to propose multidisciplinary approaches to understand landscape dynamics. In fact, trees colonizing sites of geomorphological interest are used for detecting past and present events and tree rings may be considered ecological indicators under different points of view. Arboreal vegetation can register growth disturbances in terms of morphological features, at macro - (particular morphologies of trunks) and micro-scale (annual growth rings, stress indicators like compression wood, traumatic resin ducts), becoming a powerful indicator of the geomorphic activity affecting the landscape. In some cases, combined with other techniques like climate data analysis, they may allow refining the often lacunose historical records of geomorphic events impacting different territories. The integrated analysis carried out in the Loana Valley (Sesia Val Grande Geopark, Western Italian Alps), considering a selection of geomorphosites affected by mass wasting processes and avalanches and located along a touristic trail, allow to detect which meteorological thresholds favour hydrogeological instability (i.e. overcome of Mean Annual Rainfalls of 6-10%). Tree rings data coming from the investigated sites provided information on the recurrence of geomorphic activity allowing filling gaps within the historical archives by individuating years during which hydrogeological or snow-related events probably occurred and that were missed (i.e. 1986, 1989, 2001, 2007), and providing details on sites for which temporal constraints had not been found before (i.e. Pizzo Stagno Complex System). Finally, investigated sites demonstrated to differently record the history of instability affecting the area and this difference is mirrored in the sites values that are adopted in the framework of geoheritage analysis (*Scientific Value*, *Ecological Support Role* and *Educational Exemplarity*). The proposed multidisciplinary approach, including geomorphology, dendrogeomorphology and climatology, represents, hence, a useful tool in geoheritage valorisation and management strategies.

Keywords: Geomorphic activity indicators; Dendrogeomorphology; Geoheritage; Ecologic Support Role; Loana Valley (Western Italian Alps)

1. Introduction

Geomorphic processes, as well known, can represent hazard and risk for people, including both residents and users (e.g. tourism), and also for cultural and natural heritage (Cendrero and Panizza, 1999). According to

Panizza and Piacente (2003), natural heritage includes geoheritage (sensu Osborne, 2000), which consists of ecosystem abiotic components at different spatial scale, from rocky outcrops to landscapes. Great attention is nowadays paid to landforms and geomorphological sites most representative of active geomorphic processes, (Reynard et al., 2007; Pelfini and Bollati, 2014) which are responsible for hazards. When such geomorphological evidences are characterized by specific attributes (*Scientific*, *Additional*, *Global Values* and *Potential for Use*; see a review in Brilha, 2016), they can be considered *geomorphosites* (sensu Panizza, 2001), or more precisely *active geomorphosites* or *evolving passive geomorphosites* (sensu Pelfini and Bollati, 2014). In this sense, mountain geomorphosites, particularly sensitive to climate change, represent a key-category (Giardino and Mortara, 1999; Bollati et al., 2016; Reynard and Coratza, 2016; Bollati et al., 2017a, b).

The ecological meaning of geomorphosites is of a great interest both for the specificity of endemic flora associated to specific geologic bedrocks and for the meaning of geomorphosites in environmental reconstructions. In this framework, the classification of the ecological connotation is quite different: Panizza (2001) and other Authors (e.g. Pralong and Reynard, 2005; Garavaglia et al., 2010; Pelfini et al., 2010; Bollati et al., 2017a) include the "*Ecological Support Role" (ESR)* within the scientific values, while other Authors refer to it separately, as *Functional Value* (Gray, 2004) or *Ecological Impact Criterion* (Reynard et al., 2007; Pereira et al., 2008).Considering ESR among the *Scientific Values*, as discussed by Bollati et al. (2015) and reprised by Mocior and Kruse (2016), changes in vegetation (i.e. trees) colonizing a geomorphosite may influence other attributes of the geomorphosite itself, like *Representativeness of (paleo)geomorphological processes*. In fact, tree dynamics and tree rings features allow detecting and quantifying present and past landscape changes by means of multidisciplinary approaches (Bollati et al., 2012; 2016). Integrated approaches have also important implications in geo-education allowing the increasing of the *Educational Exemplarity* value of a site (Bollati et al., 2011; Garavaglia and Pelfini, 2011a).

Among the most powerful processes affecting mountain landscapes, there are mass wasting and avalanches processes (Luino, 2005; Kogelnig-Mayer et al., 2011), as documented by the high number of researches addressed to assess, estimate and model the related geomorphological hazard. Since mass wasting is strictly related to climatic conditions and trends, many researches concern the impact of climate change on this kind of geomorphological dynamics (e.g. Soldati et al., 2006; Keiler et al., 2010). More in detail, as mass transport also depends from the intensity and duration of rainfall events (Caine, 1980), the triggering meteorological conditions and thresholds for processes like landslides and debris flows are also deeply investigated (e.g. IRER, 2008; Brunetti et al., 2010). Luino (2005) for example describes precise sequences of geomorphic processes, active at different spatial scales (local or regional), following the overcoming of thresholds. Unfortunately, Global Climate Models can be difficulty downscaled at level of mountain areas because of the complex local relief and of the local climate and the meteorological variability that lead to local hydrogeological instabilities, for example localized in small catchments (Keiler et al., 2010). Also avalanches represent a hazard affecting mountain slopes according with abundance of snow, temperature gradient and slope morphology (Barbolini et al., 2011) but their relation with climate change is less clear (Bebi et al., 2009).

Complex reciprocal interactions between geomorphic processes and ecosystems have been frequently debated (e.g. Swanson et al., 1988; Pelfini et al., 2007; Viles et al., 2008). Swanson et al. (1988) categorized 4 classes of possible consequences of landforms presence and morphogenetic processes action on ecosystems in term of environmental modifications gradient and regulation of patterns and frequency of geomorphic and non-geomorphic disturbances. Considering the case of snow avalanches, Bebi et al. (2009) underlined how, for landscape management purposes, the comprehension of the ways in which avalanche disturbances affect ecosystem processes is important and how forest conditions may alter avalanche impact. In the first case the severity and return time interval of avalanches may more or less inhibit the colonization by some arboreal species, potentially threating biodiversity; in the second case, instead, forest may slow down avalanches speed or prevent their formation by stabilizing snow in starting zones (e.g. larch forest; Albert et al., 2008). The potential hazard mitigation role of trees vegetation may be considered a form of ecosystem service as suggested by Viles et al. (2008).

Besides the mitigation role of vegetation under certain conditions, trees affected by geomorphological dynamics, in the specific, are considered powerful tool for investigating spatial and temporal distribution of geomorphic events (e.g. slope instability, snow avalanches; Pelfini et al., 2006; Soldati et al., 2006; Stoffel and Bollschweiler, 2010) and the relative rates (e.g. Viles et al., 2008; Bollati et al., 2016). Besides the macro-indicators related to vegetation (its presence or absence and its growth disturbance rates), more specific studies on the micro-features in tree rings, used in the framework of dendrogeomorphology (Alestalo, 1971), may help in detecting and dating past and present geomorphic processes affecting trees, as far as a seasonal resolution (Stoffel et al., 2005). Tree rings morphological features, generally called disturbance indicators (e.g. compression wood, traumatic resin ducts, growth anomalies), allow to date past events confirming or completing the record of events where lacunose (Pelfini and Santilli, 2008; Stoffel and Bollschweiler, 2008; Luckman, 2010; Kogelnig-Mayer et al., 2011; Pop et al., 2016), occurring especially where human settlements are rare (Jakob, 2005; Barbolini et al., 2011; Văidean et al., 2015). Hence, trees, through dendrogeomorphological investigations, may become a tool not only for environmental reconstructions (e.g. Pelfini et al., 2014) but also for calibrating, at a more precise spatial scale, the models related to debris flows and avalanches, which are based on the events recurrence time (Kogelnig-Mayer et al., 2011).

In the present research, through a research carried out on a key site in the Western Italian Alps, we aimed at: i) reconstructing spatio-temporal changes in geomorphic hazardous processes (mainly landslides, debris flows and avalanches) affecting a selection of geomorphosites by applying dendrogeomorphological techniques; ii) investigating the key role of meteorological conditions triggering the investigated geomorphic events; iii) analysing the importance of arboreal vegetation as ecological indicators of environmental changes, affecting geomorphosites features (*Ecologic Support Role*) in sensitive areas as mountain regions; iv) determining how these derived information may be gathered each other and used for enhancing the

Scientific and *Global Value* of mountain geomorphosites in the perspective of a further educational and geotouristic enhancement.

The selected area corresponds to the upper portion of the Loana Valley, located in the Ossola region. This valley represents one of the most popular accesses to the Val Grande National Park and it was recognized as an ecological corridor due to its morphological features (PNVG, 2001; Bionda et al., 2011). The Loana Valley is included within the Sesia-Val Grande Geopark, ratified in 2013 within the UNESCO European Geopark Network. The valley has been selected since different touristic and excursionist trails are present and the representativeness of landforms located along the trails has been recently pointed out and quantified in literature in order to propose some geotrails (Bollati et al., 2017a).

2. Study area

The study area is represented by the upper portion of the Loana hydrographic basin (red polygon in Fig. 1). It is located in the Verbano-Cusio-Ossola Province and it covers an area of about 27 km^2. The Loana hydrographic basin is placed at the boundary between the Ticino hydrographic basin, partially developing in Switzerland, and the Toce hydrographic basin in the Ossola Valley. The Loana stream, flowing from South towards North, is a tributary of the Eastern Melezzo draining the Vigezzo Valley and flowing, toward East, into the Swiss portion of the Maggiore Lake. The reach of the Loana stream, within which the investigated sites are located, spans between 1250 and 1300 m a.s.l..

2.1 Geological and geomorphological setting

The Upper Loana Valley is located in a geological and geomorphological relevant zone because the head of the valley is interested by the presence of the Insubric Line (locally named Canavese Line) separating the Southern Alps (on the SE) from the axial part of the Alpine chain, here represented by the Austroalpine Domain (on the NW) (Bigioggero et al., 2006). The main lithologies outcropping in the area are schists, paragneiss, gneiss and locally marbles, and along the southern part of the water divide, mafic rocks like amphibolites are abundantly represented. The region is characterized by a wide deformation belt related to the presence of the Insubric Line, conferring weakness to rocks and favouring their weathering and degradation, as already reported in other areas of the Alpine region by Soldati et al. (2006). Hence, the valley is interested by an important structural and lithological control on landforms shaping. The head of the valley is characterized by an intense glacial reshaping (horns and glacier cirques; Biancotti et al., 1998) and presents a glacial transfluence area occupied, during the Pleistocene, by glaciers flowing towards south (Val Portaiola Glacier) and north (Loana Glacier) as far as the Vigezzo Valley (Hantke, 1988; Cerrina, 2002).The resulting U-shaped valley, drained currently by the Loana stream, is undergoing a reshaping due to geomorphic processes linked with water, snow and gravity action. In figure 2 a general overview on the hydrographic features of the investigated area is provided.

The Loana stream is incised mainly in the bedrock from its spring, in the south, as far as the foot of the glacial step (reach 1 in Fig. 2c). Then, a decrease of the steepness is visible along the longitudinal profile of the valley bottom (Fig. 2c) where the alluvial deposits become abundant. This reach, object of the present research and along which the investigated sites A, B, C are located (Fig. 2a and 2b), underwent, at the end of the ‘90s of the XX century, human interventions addressed to flow regulation and alluvial plain modification to facilitate grazing. These modifications are visible comparing figures 2a (1989 ortophoto) and 2b (2012 ortophoto): the braided configuration of the river course, visible in 1989 (Fig. 2a), was transformed through time in a single-channel pattern mostly confined on the eastern valley side (Fig. 2b). The reaches 3, 4 and 5 are characterized newly by a more or less relevant increase of the steepness as far as the alluvial fan, at the outlet in the Eastern Melezzo, on which the Malesco village is located. In this area, but in general in the Ossola region, mean meteorological conditions, geological features (e.g. abundant loose debris and fractured rocks) and hydrographic basin morphology (Fig. 2d) favour heavy instability phenomena and debris flow events often take place along weakness zones (Hantke, 1988; Cavinato et al., 2005; Mortara and Turritto, 1989; Luino 2005; Dresti et al., 2011). Among the most dangerous and famous events affecting the area, there are 1961, 1968 and 1978 events inducing widespread mass wasting processes all over the region. After the 1978 hydrogeological instability event, the public administration produced thematic maps on geolithology and on geotechnical and hydro-geological instability effects of the event over the whole Melezzo hydrographic basin (e.g. Bigioggero et al. 1981). The investigated reach of the glacio-fluvial valley is interested, along both the valley slopes, by mass wasting processes and avalanches that periodically affect the valley bottom and contribute to the building of very representative polygenic debris cones (sites A, B and C in Fig. 2a and 2b) that are located at the confluence between secondary streams with the main one (the Loana stream).Avalanches are among the most dangerous processes affecting slopes, mainly during spring (Barbolini et al. 2011) (e.g. 1951, 1986, 2009 and 2014 in Fig. 3) as testified by clean corridors (site D in Fig. 2a and 2b) where vegetation is removed and transported down-valley. Historical information about avalanches affecting the study area are spare and available in the General Urban Development Plan and a model for detecting areas susceptible to avalanches was tested and applied by Barbolini et al. (2011). Locally defence works were positioned at the apex of the cone (site A) upstream to the archaeological important site of the "NucleoAlpino La Cascina", whose protection is regulated within the Landscape Regional Plan (available at: http://www.regione.piemonte.it/territorio/pianifica/ppr.htm).

2.2 Geomorphological sites description

The investigated reach of the Loana Valley is characterized by the presence of a touristic trail, mainly used during summer and easily accessible thanks to the plain morphology of the valley bottom and the pleasant landscape in which it is inserted. In the winter 2016/2017 the trail was partially widened by Municipality in order to allow skiing activities, possible during winter and spring, considering the avalanches frequency. Along the trail geomorphological features document the typical mountain hazard (mass movements, avalanches) (Fig. 3), a feature to be carefully considered for an aware fruition of trails and sky runs (Bollati et al. 2013; 2017a). As outlined by Bollati et al. (2017a), the geomorphological heritage in the Loana Valley is relevant under different points of view and the geotrails proposed by the Authors cross and connect a series of potential geomorphosites representative of the geological and geomorphological evolution of the area. Three of the potential geomorphosites detected by the Authors were selected (sites A, B, C), as very interesting also for the trees distribution on their surface, in order to discuss the role of arboreal vegetation as indicator of geomorphic activity and as a key factor in the geomorphosites assessment procedures (i.e. *Ecological Support Role)*. The sites A, B and C had obtained, in the evaluation processes of the previous research, *Global Values* that are among the highest for the area. A selection of results related to the geomorphosites evaluation are reported in table 1 (for more details see Bollati et al., 2017a).

2.2.1 Polygenic debris cone of the Nucleo Alpino "La Cascina" (site A)

The site is located at the confluence between the Cavalla and Loana streams. It is characterized by a chaotic deposit with big boulders spread in a fine matrix, feed up by debris flows and avalanches. At the end of the '90s of the XX century, defence works were positioned at the apex of the cone to protect the "Nucleo Alpino La Cascina" (Malesco Municipality, 2015), located on the southern hydrographic side of the cone and undergoing protection according to the Landscape Regional Plan. The inactive main channel is well visible (white star in Fig. 4a). The northern border of the debris cone is cut by a deep channel, now inactive, while the cone foot is characterized by a scarp shaped in the past by the Loana stream and at present colonized by vegetation. The whole surface is characterized by other minor inactive channel sand by a slight creep contributing to the tilting of the trunks. Avalanches affectless frequently the area with an estimated recurrence time of 10-30 years (Malesco Municipality, 2015). The area has been classified as moderate hazard for avalanche by Barbolini et al. (2011). According to the Authors' model, only the most severe avalanche events (e.g. 1951) may interest the site eventually by-passing the defence works.

2.2.2 Airina polygenic debris cone (site B)

The polygenic debris cone, is located at the confluence between a secondary stream on the eastern valley side and the Loana stream. It is characterized by a deposits fed up by debris flows and avalanches that, locally, transport also wood (e.g. trees, trunks, branches). Here the effect of avalanches are more evident respect to the site A: avalanche corridors are particularly manifest on the southern hydrographic side of the stream. Also the Airina polygenic debris cone is characterized, in its terminal portion, by a scarp shaped in the past by the Loana stream and at present colonized by vegetation. The lateral migration of the Loana stream is prevented due to the locally flow regulation. Up-valley, close to the terrace edge, an evident extensional trench is present. The cone is crossed in the middle by one of the geotrails proposed by Bollati et al. (2017a) and it is seasonally interrupted by avalanche deposits, as those surveyed during the 2014 spring

(Fig. 3c at site D and Fig. 4d). Avalanches occur with an estimated recurrence time of 1-10 years (Malesco Municipality, 2015) and the area has been classified as severe hazard for avalanches by Barbolini et al. (2011).

2.2.3 Pizzo Stagno Complex System (landslide and polygenic debris cone; site C)

A polygenic debris cone built by debris flow and avalanches is located down-valley to the Pizzo Stagno landslide deposits, and at the confluence between the Stagno and the Loana streams. The landslide and the polygenic cone constitute the herein called Pizzo Stagno Complex system (sensu Hungr et al., 2014). Deposits of the polygenic debris cone are in fact mainly fed by debris flows and avalanches mobilizing debris of the landslide body (Cerrina, 2002). According to the landslide classification proposed by Korup (2005) and dealing with the geomorphic coupling interfaces between landslides and river channels, the Pizzo Stagno Complex System belongs to the “linear” geomorphic coupling category. The “landslide runout” results to be “accommodated along the drainage line” and “transforming into debris flows after entraining water saturated channel fill”.

Both the landslide and the debris flows are catalogued within the IFFI Project - Inventory of Landslide Phenomena in Italy as quiescent (codes 1030131200 and 1030185200) (Malesco Municipality, 2015). Especially debris flows are considered as possibly being reactivated in a time minor than 30 years. One of the most powerful event inducing mass wasting phenomena in the region and indicated by Cerrina (2002) as the responsible of the main landslide development, occurred on 7th August 1978 and a specific focus will be put on it in the present research. The landslide was reactivated in 1982 (Cerrina, 2002) when a supplementary debris transport channel was generated (Fig. 4c). The polygenic debris cone is incised by a series of debris transport channels surrounded by evident debris flows levees and these latter is characterized by chaotic deposits made by coarse debris spread in a fine matrix. Avalanches are highly frequent with an estimated recurrence time of 1-10 years (Malesco Municipality, 2015) and the area has been classified as severe hazard for avalanche by Barbolini et al. (2011).

3. Materials and methods

3.1Historical research of hydrogeological instability and avalanches events in the Ossola region

A historical archives’ analysis was performed to detect the main extreme rainfalls and related relevant events for mass wasting events and floods (i.e. hydrogeological instabilities) which affected the region (Ossola, Vigezzo and, in particular, the Loana Valleys). The main sources were: Bertamini (1975; 1978), Tropeano et al. (1999; 2006), Cerrina (2002), Mazzi and Pessina (2008), Cat Berro et al. (2014), Malesco Municipality (2015). The historical archives dated back to the XIII century, as reported by Tropeano et al. (1999) and by

Cerrina (2002), with a good detail for recent times, except for the period 2006 - 2014 for which data were not available at the time of elaboration.

3.2Climate data analysis

The climate condition of high Ossola region, where the Loana Valley is located, is driven by different factors according with the fact that the Alpine range strongly interacts with the synoptic atmospheric circulation. Nearby some of the highest peaks of the Alps, such as the Dufour peak (Monte Rosa, 4634 m a.s.l.) and the Finsteraarhorn (4274 m a.s.l.) are present. Northern winds, that are usually very dry and quite warm (known as Föhn), or southerly wet and warm winds, rich of humidity from the Po plain and the Mediterranean Sea, are among the most interesting driving factors for the local weather conditions. When Stau conditions verify, south moist and warm advection, the study area is affected by heavy and steady rain, triggering, where geological conditions are favourable, mass wasting processes like debris flows. The most long-lived and important weather station in the Ossola Valley (Nigrelli and Collemedaglia, 2012) is located at the "Osservatorio Rosmini" in Domodossola (see location on Fig. 1) at an altitude of 270 m a.s.l.. The station data, dating back to the XIX century, was supplied by the Italian Meteorological Society (SMI). The long series of Domodossola starts from December 1871, as it is the result of an accurate work of recovery from old datasets and books (e.g. annals, daily bulletins) by Bertolotto et al. (2014). Snow heights measurements started in 1872, while daily data is available since January 1883, covering 1466 months (91.2%). On 12th April, 1989 the Environmental Protection Agency (ARPA Piemonte, available on the website - www.arpa.piemonte.gov.it/) installed, an Automatic Weather Station (AWS) in Druogno (831 m a.s.l. Vigezzo Valley), located 6 km far from the study area (see location on Fig. 1) that provided data only for the time period 1990-2014. Anyway, the latter especially could give a glance idea of weather patterns, more strictly related to the study area.

Data from the Druogno AWS, show how temperatures follow a trend typical of a low-mountain location site, characterized by a mild winter (T_{min} = -2.3°C reached in January) and a lukewarm summer (T_{max} = 25.0°C reached in July). The highest temperature (i.e. 36.0°C) were recorded on 11th August 2003 and the lowest ones (i.e. -15.0°C) on 7th February 1991.

In figure 5c and 5d, the rainfall trends from the two stations, considering the different data time interval (1871-2016, Fig. 5c and 1989-2016, Fig. 5d), are reported. Rainfalls at Druogno AWS (Fig. 5d) show two peaks, one during spring and the other one during late autumn. The mean annual rainfall, evaluated since 1989, is 1642.2 mm for the period. By means of the Gaussen and Bagnouls diagram it is possible to affirm that Druogno does not suffer drought periods. The Domodossola area (Fig. 5c) reaches the maximum rainfalls value in October, well distinct from the close months (September and November).

In this framework, the datasets from both the stations were controlled using different thresholds in order to remove "not physical" or wrong values due to instrumentation problems. For the evaluation of monthly temperatures, all the daily values for each year were considered necessary, while for annual rainfalls just the

99.5% of the yearly days were considered necessary. In the considered dataset Druogno was not reliable in three years while no missing days are present in Domodossola record, confirming the reliability of this station for long term analysis (Nigrelli and Collimedaglia, 2012). The whole uncertainty introduced is in any case smaller (around 3%) than the advantages given by those years in our analysis. Any data fulfilment algorithm was applied.

Since specific meteorological conditions (i.e. rainfalls thresholds sensu Crozier, 1996), based on rainfalls duration and the rainfalls mean intensity, may be responsible in triggering mass wasting phenomena (Luino, 2005; IRER, 2008; Brunetti et al., 2010), rainfall thresholds were analysed. In fact, they are one of the parameter usually adopted in the framework of preventive alert from Civil Protection. The percentage of Mean Annual Rainfall (MAR; i.e. the ratio of daily cumulated rain and mean annual rainfall evaluated over the complete data series), to be overcome to trigger possibly mass wasting events, and representing the minimum critical daily rainfall for activating debris flows, was fixed at 6.0, according to literature indications elaborated for similar geomorphic contexts (Bertolo and Bottino, 2006; IRER, 2008). A MAR overcoming 10% was also considered to detect the heaviest episodes, as also suggested by Luino (2005).

Starting from the rainfalls data at disposal, the percentages of overcoming specific thresholds were analysed for the time interval 1900-2014. This time interval covers the availability of historical records on hydrogeological instability events for the region (1900-2005) and the data from the Domodossola observatory.

Solid precipitations are recorded mainly by stations located near dams or in the bigger cities, such as Domodossola. A very long series of daily snow height measurements, dating back to 1883 (Bertolotto et al., 2014) is at disposal. It is important to underline the difference in altitude between the station and the study site. Anyway, the general trend of snow height is comparable with peaks recorded in January, February and December (Fig. 5c). In Domodossola the mean cumulated fresh snow has constantly decreased: during the period 1873-1929 the annual mean snow is 88 cm, instead in the last period 1991-2010 is 32 cm.

The considered snow heights were calculated as the cumulate snowfalls during the months of November of each year and April of the year after. This last parameter was derived integrating Domodossola snow heights data with those elaborated by Ronchi and Nicolella (2011) for the whole Piemonte Region and covering the period 1970-2009. In fact, snow height dataset has a series of missing years, some of those are between or during the two World Wars (1932, 1934-1937, 1943-1946) and others scattered along the time records.

3.3Dendrogeomorphological analysis

Dendrogeomorphological analyses are techniques used to date respectively historical geomorphic surfaces (Mc Carthy and Luckman, 1993; Heikkinen, 1994; Bollati et al., 2014) and geomorphic events affecting trees growing on dynamic landforms (Pelfini et al., 2007; Guida et al., 2008; Kogelnig-Mayer et al., 2011; Văidean et al., 2015; Pop et al., 2016), as well as for environmental reconstructions (Pelfini et al., 2014).

Field surveys were carried out during 2014, 2015 and 2016 and during the sampling activities specimens from 77 trees were collected on the polygenic debris cones.

On these landforms the most abundant species surveyed is *Larix decidua* Mill., followed by the *Picea abies* L. Karst that diminishes significantly more the disturbance increases. The predominance of larch is due to its physiology (Albert et al., 2008): it is a pioneer species, typical of this altitudinal range, that, even if very sensitive to temperature variations (Büntgen et al., 2005), it is characterized by the capacity of surviving on infertile soil, like that characterizing polygenic debris cones. Larches survival ability under precarious conditions allows a continue recording of geomorphic disturbances in annual growth rings. Hence they become a very suitable species to bring information on disruptive events in this kind of environments. Moreover, as mentioned in the introduction, Albert et al. (2008) stress, among the ecosystem services provided by larch, the ability of mitigating avalanches and landslides hazard.

Other 24 trees of the same species, growing in a reference area not disturbed by geomorphic processes (red circle, about 3 km far away from site C, Fig. 4b), were sampled in order to compare the presence or absence of the disturbance indicators with the disturbed area to discriminate a regional (e.g. climate or meteorological) versus local causes (e.g. geomorphic activity). Samples from trunks were taken using a Pressler increment borer at a standard height of 1.30 m (breast height). Particular attention was paid to tilted trees, wounds and scars on trunks. Tree rings width were measured (accuracy of 0.01 mm) using the LINTAB and TSAP systems (Rinn, 1996) and image analysis was performed with WinDENDRO software (Régent Instruments Inc., 2001). The obtained growth curves were cross-dated with TSAP, considering the traditionally used coefficients (GLK - Gleichläufigkeit; CDI - Cross Date Index) and using also COFECHA (Holmes et al., 1986). Cross dating procedures allow dating each individual annual ring and, as a consequence, wounds, growth anomalies and finally geomorphic surfaces and events. Disturbance on arboreal vegetation were, then, quantified by analysing and dating dendrogeomorphological indicators frequently used in this kind of investigation. The indicators considered specifically in the framework of this research are the following ones:

i) *Compression Wood (CW)* (Fig. 6a, 6b): it is a particular, resistant and denser kind of wood; it was described and dated, being a response to mechanical stress induced by the tilting of the stem due mainly to creep processes and the consequent attempt by the trees of recovering the vertical position (e.g. Timell, 1986; Bollati et al., 2012);

ii) *Scars and Traumatic Resin Ducts (TRDs)*: scars (Fig. 6, c) may be produced on trunks by impact of debris as a consequence of geomorphic processes (e.g. avalanches, debris flows, rock falls) (Stoffel and Bollschweiler; 2008; Garavaglia and Pelfini, 2011b; Kogelnig-Mayer et al., 2011; Văidean et al., 2015; Pop et al., 2016). Scars are usually self-recovered with time producing a callum to avoid the contamination by external agents. A scars-related mechanical disturbance at micro scale is represented, only in certain species, by aligned resin ducts (TRDs), wider than the normal ducts, which favour the circulation of the resin produced by conifers, in particular, to remediate the damage. The dating of the damage by means of TRDs may have a seasonal resolution according to the location of the ducts within the early- or latewood (Stoffel et al., 2008; Luckman, 2010) allowing the seasonal dating and the detection of the typology of the responsible geomorphic process. In fact, according to Kogelnig-Mayer et al. (2011), TRDs located within the latewood may indicate damage from debris flows that are frequent during late summer until early autumn, instead TRDs characterizing earlywood may instead indicate damage from winter/spring avalanches. This discrimination could be fundamental in sites affected by both the processes (i.e., polygenic cones). During a second analysis phase the dendrogeomorphological results were compared with data coming from historical archives and with the meteorological data (percentage of MAR overcoming and snow height data) to detect with a higher certainty degree which kind of geomorphic processes (e.g. mass wasting or avalanches) may be responsible for the trees damages. Also a significant minor site investigated for dendrogeomorphology (i.e. site D avalanche track, Fig. 3c), that was excluded since the number of samples were not significant, was used to support other sites data.

3.4 Statistical analysis on correlation between different sources data

In order to compare the efficacy of the historical records and dendrogeomorphology data in correlation with climate series derived data, used to reconstruct the occurrence of the geomorphological events (mass wasting and avalanche events), a series of chi-square ($\chi 2$) tests were performed on the common time intervals. Concerning mass wasting, the tests were carried out on the number of historical or dendrogeomorphological events corresponding to an overcoming of the MAR greater than 6%, on the total occurrence of a MAR greater than 6%, considering, separately, both the Domodossola and Druogno meteorological stations. The time intervals considered, respectively, is 1984 - 2005 and 1990 – 2005, in order to have a complete coverage by the 3 series of data.

Starting from the assumption that the sites are indicated in literature to be characterized by different recurrence time interval for mass wasting and avalanche events (see par. 2.2), in order to compare the sensitivity of different study sites to the extreme rainfall events (based on the events with an overcoming of the MAR greater than 6% for both two weather stations) the chi-square tests among all three study sites together and by couples were carried out. The geomorphological events recorded by dendrogeomorphology for each site were analysed based on the total number of events, corresponding to an overcoming of the MAR greater than 6%, recorded using a dendrogeomorphological approach (for the period 1984-2014 for the Domodossola weather station and for the period 1990-2014 for Druogno weather station).

In the same context, the chi-square tests were performed to understand the different study sites sensitivity also to the avalanche events. Using the data of snow accumulation, we calculated when the snow accumulation was above the average (signal of possible occurrence of avalanches). The comparison among all the three sites and by couples was carried out taking into consideration the difference between the amount of snow avalanche events detected through dendrogeomorphology for each study site and the total number of events recorded by means of dendrogeomorphology.

4. Results

4.1Historical archives and Mean Annual Rainfall analysis

The most evident result, obtained by gathering between historical archives and climatic data, is the detection of the most common meteorological conditions under which the analysed typology of hazardous events usually happens (i.e. events with MAR - Mean Annual Rainfall overcoming 6-10%).
The complete list of rainfall events characterized by the fixed threshold of MAR overcoming greater than 6% is reported in Appendix 1-A. The events in the list are overcoming the fixed threshold at least in 1 of the 2 stations: Domodossola (1900-2014) or Druogno (1990-2014). In the Appendix 1-B, the list of the 10 hydrogeological instability events derived from the historical archives, but that are not characterized by a MAR overcoming greater than 6%, is reported.
The number of overcoming events is 169 for Domodossola and 49 for Druogno. Considering the common period between stations, not all the events overcoming the threshold according to the Domodossola dataset appear in the Druogno record (15.52%) and vice versa (44.83%). The remnant 39.65% are the concordant events. From the Appendix 1-A and the table 2 it emerges that among the events overcoming the MAR threshold (6%), the greatest percentage is characterized by a 6% to 10% of overcoming (85.80% Domodossola and 89.80% Druogno) while a low number exceeds the 10% threshold (14.20% Domodossola, 10.20% Druogno).
The 20% of the 175 listed events (1900-2005) are characterized by hydrogeological instability (table 2). Crossing more in detail the instability with climatic thresholds, hydrogeological events are more often associated with MAR overcoming comprised between 6% and 10% (92.90% Domodossola, 94.59% Druogno), while they are less coincident with MAR overcoming greater than 10% (6.51% Domodossola, 5.41% Druogno) or lower than 6% (0.59% Domodossola, 0% Druogno).
According to data on hydrogeological instability events reported in Appendix 1-A and 1-B and covering the time interval 1900 to 2005, the Toce hydrographic basin is frequently characterized by extreme rainfall events inducing mass wasting processes, most of them affecting the Melezzo and the Loana basins. The archives records allow noticing that several events differently affected Toce, Melezzo and Loana hydrographic basins. Sometimes (31.11%) they produced damages in at least two of the basins, sometimes (42.22%) only other than Melezzo or Loana sub-basins of the Toce one were hit and in other cases (26.67%) damages were reported only in the Melezzo or Loana hydrographic basins.
It is worth to be underlined that, as reported in Appendix 1-B, hydrogeological events 6 and 8, inducing instability at regional scale, are not recorded in the climatic record of the Domodossola station that covers their time interval.

4.2 Dendrogeomorphological analysis

Dendrogeomorphological investigations on arboreal vegetation colonizing the investigated sites (A, B, and C) allowed detecting which kind of events affected them during times. Tree vegetation colonizing such deposits, whose spatial distribution is shown in figure 7, is generally younger than 30 years, indicating a persistent geomorphic activity cyclically affecting trees. Hence, the events that may be observed in tree rings record are those characterizing the last 30-40 years' time interval. The dendrogeomorphological data cover respectively the time intervals 1984-2014 for the site A, 1983-2014 for the site B and 1975-2014 for the site C. In all the investigated cases, the vegetation is not homogeneously widespread on the sites surfaces testifying the different spatial distribution and intensity of geomorphic processes. In Appendix 1-A, 1-B and in the table 3 details on tree rings data at site A, B and C are reported in relation with the events reconstructed by means of mass wasting and avalanches historical archives and climate data analysis. The description of the dendrogeomorphological achievements for each sites is reported in the following subparagraphs (4.3.1,2,3).

4.3.1 Polygenic debris cone of the Nucleo Alpino "La Cascina" (Site A)

The polygenic debris cone may be split in two portions defined by the Cavalla stream position and history:

i) the northern part of the cone is comprised between the Cavalla stream and the inactive channel located in between the cone and the mountain side. This portion is abundantly colonized by trees (Fig. 7a), quite homogeneously distributed, with the older one dating back to 1984;

ii) the southern portion is inactive, as the result of defence works; nevertheless, it does not present a tree coverage also as a consequence of the intense human interventions.

The common period for the 17 analysed tree rings series is 1994-2014. The trees located at the cone apex are the younger and more disturbed ones. TRDs, scars and CW data are reported in figure 8a. TRDs are present in the years 1986, 1994, 1999-2000, 2003-2009, with a peak of abundance in 2005 and 2009. The seasonal subdivision among TRDs shows a predominant presence within latewood and at the border between earlywood and latewood in 2005, 2009 and presence in 1986, 1994, 1999 and 2004. Earlywood presents TRDs in the years 2000, 2003-2007 and 2009. The scars observed dated back to 1986, 1995, 2004-2005 in relation with TRDs and a peak of scars number is recorded in 2004 and 2005. CW is detected all along the time interval 1986-2014 and the peaks of abundance are in the 2004-2009 time intervals.

4.3.2 Airina polygenic debris cone (site B)

The Airina cone is mainly colonized by trees on the fluvial erosion scarp (Fig. 7b), where they seem to be protected by the avalanche events that affect instead the central-southern portion, as documented by the absence of trees. On the central-southern portion of the cone surface abundant dead wood debris is present. These dead trees are transported on the cone surface by the recurring avalanches, since their cambial ages

(100-300 yrs) suggest they come from the upper portion of the slope where trees show the same age as the one living in the reference area. The common period for all the tree growth curves is 1992-2014 while the oldest tree dated back to 1987. TRDs, scars and CW data are reported in figure 8b. TRDs are present during the years 1984, 1994-1995, 1998-1999, 2003-2007 and in 2013 and show a greater abundance in 1994, 2003-2004 and 2007. TRDs are present within the latewood and at the border between earlywood and latewood and they are recurrent during 1994, 2004-2005, 2007 while earlywood TRDs are prevalent during the year 2003, followed by the years 1994-1995, 1998-1999, 2004, 2006 and 2013.The observed scars date back to 1994, 2003, 2005 and 2006 and are associated with TRDs. CW results to be present all along the time interval 1986-2014; peaks of abundance are recorded in 1998-1999, 2009-2010 and 2014.

4.3.3 Pizzo Stagno Complex System (landslide and polygenic debris cone; site C)

Trees age spatial distribution is quite different also between the southern and the northern portion of site C (Fig. 7c). The common period of the chronologies is 1999-2014. The southern portion of the cone is characterized by older (about 40 years old) and less disturbed trees while the northern portion is colonized by younger trees (less than 20 years old) whose growth curves are very variable testifying the local diversity in geomorphic dynamics. Anyway, a uniform arboreal colonization phase started, also in the northern part of the cone, in 2000 after a period of heavy geomorphic instability that probably prevented trees growth. TRDs, scars and CW data are reported in figure 8c. TRDs are very abundant and constantly characterize the annual tree rings pattern in the study site. They are particularly numerous in the years 1977, 1981, 1983-1984, 1986-1990, 1998, 2000-2005 and 2007-2014, with peaks during 2003-2005, 2007, 2011 and 2014. It is worth to be noticed that it is the only site reporting TRDs in the earlywood of the year 2015. Nevertheless 2015 was not considered for quantitative analysis because the sampled year is incomplete. A very clear distinction was found between trees affected by TRDs during the ‘80s (1983-1990), located on the currently inactive southern side of the polygenic debris cone, and trees interested by growth disturbance mainly after 2000, located on the currently active northern side of the polygenic debris cone. More in detail, TRDs located within latewood and at the border between earlywood and latewood are particularly present during 2003-2005, 2007 and 2010, while earlywood TRDs dominate during 1987, 2003-2005, 2007, 2010-2011 and 2014. The scars observed dated back to 1983, 2004-2005, 2007, 2010-2011 and 2014, with a peak in 2005, and they are accompanied by TRDs. CW is present all along the time interval (1975-2014) and the peaks of abundance are recorded in the time period 2003-2014. CW results concentrated in particular in trees located in correspondence of the debris flow channels.

4.3.4 Correlation between climatic, historical archives and tree rings data

Considerations regarding the possible correlation between tree growth disturbance and geomorphic processes induced by extreme rainfalls events and/or snow avalanches were elaborated starting from the assumption that indicators like TRDs in latewood may be related with debris flows, while those in earlywood may be more probably associated with avalanches (Kogelnig-Mayer et al., 2011). By integrating datasets on rainfalls and snow heights, the attribution to the most probable disturbance affecting trees was possible.

Globally, as results from Appendix 1-A, 1-B and in table 3, during the different time intervals covered by the tree rings series, the Druogno station data are better concordant with trees indicators (e.g. at site C 26.53% recorded events) than Domodossola data (e.g. at site C 13.95% recorded events). The highest percentage of hydrogeological instability events and disturbance in tree rings is recorded at site C (44.44%) with a relevant gap respect to other sites (site A, 14.29%; site B, 16.67%).

Analysing hydrogeological instability events associated with overcoming of threshold, those provoking trees disturbances in at least one site are the following ones (numbers in Appendix 1-A):

- A: 149 (1994)
- B: 149 (1994)
- C: 133 (1987), 165 (2000); 169 and 170 (2002)

Events during which MAR thresholds were overcome but that are not characterized by hydrogeological instabilities and trees were damaged at least in one site are (numbers in Appendix 1-A):

- A: 161 (1999), 162 (2000), 171 (2002), 173 (2004), 175 (2005)
- B: 128 (1984), 148 and 150 (1994), 151 (1995), 156 and 158 (1998), 161 (1999), 171 (2002), 172 (2003), 173 (2004), 175 (2005)
- C: 110 (1977), 135 (1988), 138 (1990), 158 (1998), 163 (2000), 171 (2002), 172 (2003), 173 (2004)

An event during which MAR threshold was not overcome but that is reported for hydrogeological instability and damages at trees in site C is the event 10 (2005; Appendix 1-B).

According to the detected correspondence between MAR thresholds, hydrogeological stability events and tree rings, additional hydrogeological instability events can be hypothesized only from damages in tree rings:

- A: Late Summer-Autumn 1986
- C: Late Summer-Autumn 1986, 1989, 2001, 2007.

Concerning results on avalanches, reported in figure 9, they derived from the integration between historical archives, field surveys, ortophotos analysis, snow heights from Domodossola station and Ronchi and Nicolella (2011) and the indicators in tree rings data for the time interval 1974-2010. Historical archives regarding avalanches and ortophotos observations provided few data on avalanches (e.g.1951, 1986, 1999, 2009). Several snow heights data are missing and, for this reason, the results indicated for tree rings were deduced considering also the dataset elaborated by Ronchi and Nicolella (2011). The graph and the table including the different number of recorded events for each site in the common period 1983-2011 are reported in figure 9. As already mentioned (Fig. 3), the 3 sites do not record with the same pattern the avalanches potentially affecting the sites (site A36.36, site B 27.27% and site C 63.64%). 2003-2004, 2004-2005, 2006-2007 look like to be the periods most impacted by snow avalanches.

Moreover, the period 2002-2003 might be also indicated as possibly characterized by disturbs due to avalanches at site A due to the presence of earlywood TRDs.

4.3. Statistical analysis on data correlation

Observing the data obtained by the comparison of two methods (i.e. historical record and dendrogeomorphology) used to reconstruct the past geomorphological events, the difference between the number of total events detected is evident during the time interval considered for each meteorological station (Appendix 1-A; Fig. 9; table 4).

For the Domodossola weather station (1984-2005), starting from a total of 33 events the historical records report 5 events, whereas the dendrogeomorphological data show the occurrence of 13 events. Also using the Druogno weather station data (1990-2005), starting from a total of 31 events the historical records report 5 events, whereas the dendrogeomorphological data record the occurrence of 14 events. The chi-square tests, calculated starting from the rainfall events overcoming the thresholds of MAR greater than 6% for both the two weather stations (Domodossola and Druogno) (table4), show that the two methods used to reconstruct the past geomorphological events are significantly different: $p<0.05$.

The comparison among the different study sites sensitivity to geomorphological processes due to extreme rainfall events, carried out applying dendrogeomorphology, shows that the site C has detected the largest number of events (10 for Domodossola station and 13 for Druogno station) (Appendix 1-A). The chi-square tests, performed on all three study sites together and by couples, are significant at the $p<0.05$ level only for the comparison among all the three study sites together and for the comparison between site C and A, carried out starting from the Domodossola weather station data (table 5).

Finally, considering avalanches record, the comparison among all three study sites together and by couples reveals that the site C has detected the largest number of avalanches (Fig. 9) but the chi-square tests are not significant at the $p<0.05$ level (table 5).

5. Discussions

5.1 Climate, geomorphological and dendrogeomorphological data integration

The historical archives of hydrogeological damaging events are characterized by the great limit of missing information especially for remote area, were no permanent infrastructures are located and for which news regarding mass wasting and avalanches have been rarely published (e.g. Barbolini et al., 2011; Văidean et al., 2015). This is the case of Loana Valley where the car way to get the area was built only during the ‘70s of the XX century. Nowadays the valley is frequented mainly during late spring until late October, as avalanche frequently interrupt the access road. According to the obtained results, different kind of sources (i.e. historical archives on instability events and snow avalanches, climate data from historical archives or AWSs and tree rings) resulted to be suitable to be gathered together for filling in these gaps.

Different considerations may be done on the variable correspondence between sources.

In general, the analysed typology of hazardous events (i.e. mass wasting processes) demonstrate to be common (85.80% for Domodossola and 89.80 % for Druogno AWS) under meteorological conditions when MAR overcoming is comprised between 6% and 10%.

When climate, historical archives and tree rings coincide, it means that instability affected certainly the studied area. When climate and historical archives are concordant but tree rings do not report any disturbance, the hydrogeological instability should have affected different areas. In particular, in this category, one of the most devastating hydrogeological instability event is included: number 114 (Appendix, 1-A) – 7th August 1978. According to Cerrina (2002), the landslide at site C was activated during this significant event. Data coming from dendrogeomorphology does not seem to support this hypothesis. No historical archives reported this information except for personal communications, the Regione Piemonte thematic maps produced after the event indicate the instability as already present before the event as well as the historical aerial photos of the Geographic Military Institute (IGM) preceding the event (1954, 1970).

Concerning hydrogeological instabilities reported in archives but coincident with neither climate nor tree rings data (i.e. 1-9; Appendix 1-B), according to their typology, they could have affected other areas and be associated to other kinds of control factors not mandatorily needing extreme rainfalls for mobilizing debris (e.g. structural, freeze-thaw cycles). In fact, it is worth to underline that the effects of meteorological events depend also on the typology of the meteorological event itself and local conditions for hydrogeological instabilities are common in mountain areas, as driven by microclimate and local relief settings (Keiler et al., 2010). Finally, extreme meteorological events do not automatically provoke instabilities as testified by those events not recorded as instabilities or as tree ring growth anomalies (e.g. number 134, 1987; Appendix 1-A).

In this analysis the local limitation of tree rings record emerges (e.g. climate and historical archives coincide each other but not with tree rings), as well as the lacunae affecting the historical archives that usually report events mainly affecting most populated areas, disregarding remote areas, like the studied one. As a confirm, the statistical comparison among sets of data indicates that dendrogeomorphological and historical archives are significantly different concerning their correspondence with the extreme rainfalls events, being, however, the dendro-record more complete (Stoffel and Bollschweiler 2008). Within this research it was possible to detect potential instabilities from tree rings records (see par. 4.3.4) even when meteorological and/or the historical record report any event. For example, site C recorded disturbances during the meteorological event number 161 (1999) but no information is included in historical archives.

Apart from the local reliability of tree rings data, the main limit encountered during the tree rings analysis regards the young trees age that is related to the dynamic geomorphic context. Older trees are locally preserved and allow collecting information about older events which affected the area only where the snow tracks and debris directions changed through time, as in the case of the site C. Trees ages reduce the possibility to extend to the past the coupling of information from tree rings with ones from the historical data and with the data on meteorological conditions responsible for geomorphological instability events.

Also the statistical results are affected by the limit of the number of data (i.e. years) at disposal. In fact, even if the site C detected a greater number of events, a significant sensitivity differences among different study sites in detecting events are found only for what concerns the comparison among all sites together and between site A and C, carried out starting from Domodossola weather station (table 5).

Tree rings dataset indicate a period of major disturbance, common to the three study sites, during the middle of ‘90s of the XX century and the 2002-2005 time interval. As reported in literature (Keiler et al., 2010), widespread hydrogeological instabilities all over the Alps, especially in Eastern part, were recorded during 2005 with the occurrence of several debris flows and landslides triggered by critic meteorological conditions. In that period also the Loana hydrographic basin was probably affected too, as mentioned in historical archives (Appendix 1-A). The fact that the year 2005 was not recorded evidently in the climate dataset may be related to extreme spatial variability in weather conditions in small catchments in mountain areas as mentioned before (Keiler et al., 2010). In the northern portion of the site C, the more complete site in term of presence of indicators related to geomorphic disturbance, the instability concerning the2003-2005 time interval seems to be recorded by trees since recent times. The site C is characterized up-valley by a more instable context, due to the presence of a landslide body that may act as powerful debris-feeder, connecting with the fluvial system (Korup, 2005), favouring greater damages to trees.

The site A, where defence works are present since the ‘90s of the XX century for protecting the southern hydrographic portion of the cone where the “Nucleo Alpino La Cascina” is located, the disturbance on trees is rarer (table 3): the values of number of recorded events is always lower that in the sites B and C. It is anyway characterized by disturbance on the northern portion during recent times even if with a lower intensity.

Concerning avalanches, the historical record is lacunose and the snow heights obtained integrating the two main sources (Domodossola station and Ronchi & Nicolella, 2011) have been here considered as the most reliable data. The general avalanches hazard degree, derived from the model for avalanches elaborated by Barbolini et al (2011), indicate a return time of 1-10 years, while from tree rings data it is possible to presume a shorter time span, at least of 1-5 years, for events able to produce damages at trees sites. Finally, tree rings, and especially TRDs, can be used to fill in some gaps existing in the record of this kind of events as already demonstrated for example by Stoffel and Bollschweiler (2008) and by Văidean et al., (2015).

The present research evidences how different sources of data, biological (i.e. tree rings) or abiological (geomorphological evidences, climate datasets and historical archives), represent very precious indicators to be gathered in the framework of hydrogeological instabilities and avalanches analysis.

5.2 Ecological meaning of the investigated geomorphosites and fallouts for geoheritage analysis

Arboreal vegetation is one of the elements of the ecosystem that suffer complex interactions with geomorphic processes (Swanson et al., 1988; Viles et al., 2008). Different authors (e.g. Albert et al., 2008; Bebi et al. 2009), especially considering larch dynamics, underlined how landslides, debris flows and avalanches affect ecosystem processes and how forest conditions may alter these disturbances. The potential hazard mitigation role of arboreal vegetation is also considered by Viles et al. (2008) a form of ecosystem service. In addition, as demonstrated in the present research, tree rings data combined with geomorphological, climatic and historical archives data, may become a reliable resource also in the framework of geoheritage studies. Arboreal vegetation witnesses and documents the dynamicity of the physical landscape allowing detailing the geomorphological and paleo-geomorphological representativeness of sites of geomorphological interest. This opens the discussion on the meaning of the analysed mountain geomorphosites from an ecological point of view in the framework of geoheritage. Evaluation of attributes of geomorphosites (e.g. *scientific*, *cultural*, *socio-economic*) is crucial for the assessment of the global values of geomorphosites and for the selection of sites and/or geotrails for valorisation, dissemination and educational purposes (e.g. Bollati et al., 2017a). Tree rings analysis on geomorphosites outline the importance of the *Ecological Support Role (ESR)* in particular in geoheritage assessment and increase the *Scientific Value* (e.g. *Representativeness of (paleo)geomorphological processes*) of the sites (Bollati et al., 2015; Mocior and Kruse, 2016) thanks to the dendrogeomorphological reconstructions. Moreover, tree rings data, and dendrogeomorphological reconstruction of past events, increase the *Educational Exemplarity* of geomorphosites since they can be used for multidisciplinary educational applications concerning both the environmental change (e.g. Garavaglia and Pelfini, 2011a; Bollati et al., 2011) and, consequently, geo-risk education (e.g. Giardino and Mortara, 1999; Coratza and De Waele, 2012; Bollati et al. 2013; Alcantara-Ayala and Moreno, 2016). At this scope a key role is played by the ability in raising interest in common people and students for knowing the landscape and its geomorphic dynamics. A possible approach should consider the knowledge about the relationship existing between landforms evolution, processes and responses of the ecosystem becoming of great importance for cultural tourism in mountain areas.

In this sense, the three study sites were detected and evaluated as geomorphosites (Bollati et al., 2017a), and, as mentioned before, they obtained high *Global Value* and in particular high *ESR* within the *Scientific Value* (table 1). The sites are distinct from both geomorphic and dendrogeomorphological point of view, as well visible in figure 3, where avalanches intensities appear different at the sites, as also confirmed by models elaborated by Barbolini et al. (2011).

Starting from the assumption that the sites are characterized by different recurrence time interval for mass wasting and avalanche events (see par. 2.2), as resulted also from tree rings data, the potentiality of the sites and related trees in recording events was investigated in terms of distribution and response to geomorphic disturbs of the arboreal vegetation colonizing the sites. This was aimed at identifying the site most suitable to illustrate the most complete series of geomorphic events affecting the area.

The main achievements for each site are summarised as follows.

Geomorphosite A is characterized by two portions that are differently active, due, in this case, to the defence works. Trees are distributed quite homogenously on the northern hydrographic portion of the site and recorded geomorphic activity. Anyway, their presence and appearance testify that these events could be considered not so disruptive. This site may be classified as an active or more precisely quiescent geomorphosite according to Pelfini and Bollati (2014) with an inactive southern portion due to defence works. There is a cultural site located on the polygenic debris cone that adds a *Cultural Value* to the sites itself. Moreover, the management of human settlements respect to geomorphic hazards represent a key dissemination point at this site;

Geomorphosite B is an active geomorphosite according to Pelfini and Bollati (2014). It is colonized by trees only in the distal part in correspondence of the scarp generated by the fluvial erosion, while the other part is quite totally trees-free. Even if avalanches have been recently surveyed on the field (e.g. 2009, 2014) the vegetated portion of the landform does not seem to be impacted deeply by avalanches, as emerged from the rare presence of TRDs or scars. Avalanches generally affect the southern hydrographic portion of the cone where they totally remove the arboreal vegetation coverage, deleting the possibility of recording any event. The geotrail, object of analysis by Bollati et al. (2017a), crosses in the middle the site B. The site is meaningful, in safety condition, for *Educational Exemplarity* since trees may be used to track and to show the perimeter of the most recurrent avalanche events.

Geomorphosite C is complex and constituted by a polygenic debris cone connected up-valley with a landslide body (linear geomorphic coupling; Korup, 2005). The distinction between the activity degree on the southern and northern portions of the cone is once again reinforced by arboreal vegetation analysis: the southern portion is characterized by older trees and TRDs affected them only during the ‘80s of the XX century while the northern portion is characterized by younger trees and TRDs are, as a consequence, recorded only during the last 15 years. In the site C the disturbance appears to be more continuous and deeper for the already mentioned presence upstream of the landslide body that make this site very peculiar. Cerrina (2002) indicates that the 1978 event (114 in Appendix 1-A) might be responsible for the landslide genesis but no disturbances were recorded by trees during that period, as described before. However, according to Cerrina (2002), one the event characterizing the 1982 year, (123, Appendix 1-A) may be considered as the cause of the opening of the secondary debris-transport channel. The percentage of recorded events when hydrogeological instabilities is greater than in the other sites (44.44%) and especially the statistical comparison with site A is statistically relevant ($p<0.05$; table 5). The highest *Global Value* among the three sites, obtained in the previous research (table 1), is confirmed by the tree rings analysis presented in this research so that the *ESR* of the landforms may be outlined, as well as the possibility of using the site to describe a more complete history of geomorphic events affecting the area.

The distinction among sites, which using the methodology of Bollati et al. (2017a) obtained the same ESR value (0.67) may suggest the possibility of inserting a greater detail in the evaluation procedures concerning *ESR* parameter, sometimes not even included. This suggestion may allow to differentiate sites also from ecological point of view, with the aim of reconstructing the more complete records of geomorphic events in an area.

For summarising, in figure 10 a flow diagram shows the relations between the tree rings as ecological indicators and the geoheritage and it shows also how tree rings analysis may be crucial for geo(morpho)heritage assessment procedures. Linking analysis for calculating geomorphosites value and for their mapping with the information coming from trees as ecological indicators, may have the fallout of possibly: i) performing geohazard assessment and, as a possible consequence, of setting up education practices to raise public awareness of geomorphic processes during both quiescence or emergency time (i.e., usable science; Giordan et al., 2015); ii) structuring multidisciplinary geoeducation opportunities including both biological and abiological features to support people in perceiving landscape as a whole.

6. Conclusions

The results obtained in the framework of this research allow to highlight how tree rings may represent ecological indicators of geomorphic activity in geoheritage studies. The role of ecological indicators played by trees emerges from the sequences of investigations carried out: i) analysis of statistical and empirical relationship existing between different kind of data (historical archives, climatic and dendrochronological data); ii) dendrogeomorphological reconstruction of instability events recurrence affecting geomorphosites for refining the historical archives and climatological data; iii) analysis of the fallouts on the evaluation of geomorphosites, representative of the mountain environment and characterized by mass wasting and avalanche processes. Results allowed detecting which meteorological thresholds favour hydrogeological instability (i.e. overcome of Mean Annual Rainfalls of 6-10%). Tree rings data allowed also filling gaps within the historical archives by individuating years during which hydrogeological or snow-related events probably occurred and that were missed (i.e. 1986, 1989, 2001, 2007), providing details on sites for which temporal constraints had not been found before (i.e. Pizzo Stagno Complex System). Results pointed out how *Scientific Value* and in particular *Ecological Support Role* and *Educational Exemplarity* in geoheritage assessment procedure, benefit from this integrated analysis approach. Finally, the interconnection between different research topics (geomorphology, dendrogeomorphology, climatology and geoheritage analysis) demonstrated to provide a more comprehensive framework for further valorisation and management strategies addressed to geoheritage.

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Tables

Table 1

Geomorphosites description and numeric values. The results obtained through the quantitative assessment presented in Bollati et al. (2017a) are reported together with a brief description of the geomorphic features. The maximum value obtainable for each parameter is indicated. The codes used for naming sites in the present research are indicated together with those used by Bollati et al. (2017a). List of acronyms as used in Bollati et al. (2017a): SV = Scientific Value, AV = Additional Value, GV = Global Value, PU = Potential for Use, SIn = Scientific Index, EIn = Educational Index.

	Code (present research)	Code Bollati et al. (2017a)	**SV**	**AV**	**GV**	**PU**	**SIn**	**EIn**
Geomorphosites investigated by means of tree rings analysis	**A**	G1	4.67	2	6.67	7.6	0.33	0.66
	B	G3	4.67	2	6.67	8.44	0.33	0.81
	C	G6	6.17	2	8.17	7.88	0.66	0.76
Geomorphosite for comparison of the results	**D**	G4	3.67	1	4.67	7.44	0.33	0.48
	Maximum Values obtainable		*8*	*3*	*11*	*12*	*1*	*1*

Table 2

Results of the comparison analysis, over the common periods, between meteorological and hydrogeological instability events coming from respectively Domodossola and Druogno stations and the historical records coming from the different sources indicated along the text.

CLIMATIC THRESHOLDS			**CLIMATIC THRESHOLDS& HYDROGEOLOGICAL INSTABILITY**		
	Domodossola station (1900-2014)	**Druogno station (1990-2014)**		**Domodossola station (1900-2005)**	**Druogno station (1990-2005)**
Total record (>6%)	*169*	*49*		*169*	*37*
Thresholds	> 10%	> 10%	*Thresholds*	> 10%	> 10%
N° events	24	5	*N° events*	11	2
Total record (>6%)	**14.20**	**10.20**	*% Events*	**6.51**	**5,41**
Thresholds	6%-10%	6%-10%	*Thresholds*	6%-10%	6%-10%
N° events	171	51	*N° events*	183	54
% Events	**85.80**	**89.80**	*% Events*	**92.90**	**94,59**
HYDROGEOLOGICAL INSTABILITY (historical record: 1900-2005)			*Thresholds*	< 6%	< 6%
Total record	*175*		*N° events*	1	0
% Events	**20.00**		*% Events*	**0.59**	**0**

Table 3

Results of the comparison analysis, over the common periods, between tree rings and meteorological events coming from respectively Domodossola and Druogno station and the historical records coming from different sources indicated along the text.

TREE RINGS RECORDED EVENTS						
	A (1983-2014)		**B (1984-2014)**		**C (1975-2014)**	
N° potential events	70		68		92	
N° events in trees	9		14		17	
% Events	**12.86**		**20.59**		**18.48**	
TREE RINGS & CLIMATIC THRESHOLDS EVENTS						
	A		*B*		C	
	Domodossola (1983-2014)	**Druogno (1990-2014)**	**Domodossola (1984-2014)**	**Druogno (1990-2014)**	**Domodossola (1975-2014)**	**Druogno (1990-2014)**
N° events(>6%)	45	49	43	49	67	49
N° events(>6%) in trees	3	8	6	11	11	13
% Events	**6.67**	**16.33**	**13.95**	**22.45**	**13.00**	**26.53**
TREE RINGS & HYDROGEOLOGICAL INSTABILITY EVENTS						
	A (1983-2005)		*B (1984-2005)*		C *(1975-2005)*	
N° events	7		6		9	
N° events in trees	1		1		4	
% Events	**14.29**		**16.67**		**44.44**	

Table 4

Values of chi-square tests obtained by analysing the sensitivity of two methods (historical records and dendrogeomorphology) to detect the geomorphological events due to extreme rainfall events overcoming the 6% MAR threshold measured based on the two different weather stations data.

Historical records vs dendrogeomorphology	χ^2	**d.f.**	**P value**
Domodossola weather station	4.89	1	<0.05
Druogno weather station	6.15	1	<0.05

Table 5

Values of chi-square tests obtained by analysing the sensitivity of different study sites in detecting the geomorphological events due to extreme rainfall events measured based on two different weather stations data and in detecting the avalanche events due to extreme snowfall accumulation.

		χ^2	**d.f.**	**P value**
Domodossola weather station	All the sites	6.21	2	< 0.05
	A vs B	1.36	1	0.244
	B vs C	1.89	1	0.169
	A vs C	6.10	1	< 0.05
Druogno weather station	All the sites	2.14	2	0.343
	A vs B	0.78	1	0.376
	B vs C	0.33	1	0.564
	A vs C	2.12	1	0.146
Avalanche events	*All the sites*	3.86	2	0.145
	A vs B	0.23	1	0.629
	B vs C	3.60	1	0.058
	A vs C	2.10	1	0.147

Figure captions

Fig. 1. Location of the study area in the Western Italian Alps, within the Verbano-Cusio-Ossola province, at the border of the Val Grande National Park and within the Sesia-Val Grande Geopark. The portion of the Loana hydrographic basin investigated in the present research is represented in red. The yellow stars indicate the position of the meteorological stations whose data were used in the present research.

Fig. 2. Loana stream patterns and location of the investigated sites A, B and C. a) Loana braided reach during the 80's (ortophoto of 1989 courtesy of Geoportale Nazionale–Ministero dell'Ambiente); b) Loana stream pattern several years after human intervention for flow regulation and grazing surface realization (ortophoto of 2012 courtesy of Geoportale Nazionale–Ministero dell'Ambiente); c) longitudinal profile of the Loana stream from the source to the outlet in the Eastern Melezzo as derived from the DTM (10 m) (courtesy of Geoportale Regione Piemonte). The profile is subdivided in reaches according to evident slope variations; study sites are located in the reach n. 2 (white star); d) Slope map derived from the DTM (10 m) (courtesy of Geoportale Regione Piemonte) with reported the main hydrographic basins and streams draining the region. On this map. the numbers of the reaches related to figure 2c are reported.

Fig. 3. Magnitude and effects of the avalanches events affecting differently the investigated sites (A, B, C and also D) on the Google Earth image of 2014 and appreciable from the field photos. Google Earth image: the snow thickness in site A is very low; the deposits cover mainly the upper and southern portion of the site B; in sites C and D snow coverage is consistent. Field photos: in site C the snow thickness is greater than in the other sites and the tilting of the stems and the valley-prone trees canopies are evident; in site D there is a marked areal avalanche corridor but the corresponding results are not described in detail in the present research and only used for comparison. One of the geotrails proposed by Bollati et al. (2017a), visible in yellow on the Google Earth image and in the field images of sites B, C and D, is interested seasonally by hazardous processes and specific geomorphological hazards prevention measures should be adopted.

Fig. 4. The 3 study sites and, in the middle, a panoramic view of the reach of the Loana Valley investigated in the framework of the present research. a) The polygenic debris cone of the "Nucleo Alpino La Cascina" (Site A); b) general overview on the Loana stream reach; c) the polygenic debris cone and the landslide body and scar of the Pizzo Stagno landslide (Site C); d) Airina polygenic debris cone (site B). The red circle in figure b indicate the site used as reference in dendrogeomorphological analysis (see paragraph 3.3).

Fig. 5. General overview on the annual meteorological patterns of the study area from the two weather stations at disposal. a) Temperatures, b) Snow heights and c) Rainfalls from the Domodossola Observatory (Bertolotto et

al., 2014; from December 1871 to December 2016); d) Rainfalls from the Druogno AWS (from April 1989 to December 2016).

Fig. 6. Examples of micro- and macro-disturbances on *Larix deciduas* Mill.. specimen in the study area. a) Compression wood indicated by arrows on a tree core; b) a tilted and deformed trunk; c) a decimetre scar.

Fig. 7. Geomorphological sketches (on the left) and ortophotos of 2009 (courtesy of Provincia Verbano-Cusio-Ossola) (on the right) with the spatial distribution of the sampled trees. The main geomorphological elements (debris flow channels and avalanche corridors) are indicated as well as the geotrail crossing landforms.

Fig. 8. Graphs reporting the temporal distribution of dendrogeomorphological indicators (TRDs. Scars and CW) for the 3 studied sites (a. site A; b. site B; c. site C). L_TRD, TRDs in latewood; E/L_TRD, TRDs at the edge between early- and latewood; E_TRD, TRDs in earlywood; (L)/E_TRD, TRDs at the edge between late- and earlywood; CW, compression wood.

Fig. 9. Number of dendrogeomorphological sites affected by avalanches in comparison with the maximum number of sites recording during each year. The below table reports the number and percentage of events recorded at each sites.

Fig. 10. The role of tree rings as ecological indicators in the framework of geoheritage analysis. The geoheritage analysis and communication images are reprised from Bollati et al. (2017a).

Appendix caption

Appendix 1. List of the meteorological events related to the time interval 1900-2014, considering the Mean Annual Rainfalls (MAR) overcoming and the historical events characterized by hydrogeological instability gathered with the tree rings record at sites A, B and C. Meteorological events, obtained from data of rainfalls derived from Domodossola Observatory and Druogno meteorological stations, are reported with the corresponding MAR %. In Appendix 1-A, the events overcoming the MAR at least for 6% in at least 1 station are reported. In Appendix 1-B, the hydrogeological instability events not overcoming the MAR threshold of the 6% are reported, indicating it as “min”. Historical records are compiled according to the databases reported in Bertamini (1975; 1978), Tropeano et al. (1999; 2006), Cerrina (2002), Arpa Piemonte (2008), Mazzi and Pessina (2008), Cat Berro et al.(2014) and Malesco Municipality (2015). Dendrogeomorphological events are indicated as 1 when finding correspondence with climate and/or historical records. Dark grey indicates the events finding correspondence between the historical record of geomorphic events and climate series data with MAR overcoming greater than 6% (Appendix 1-A), light grey, on the contrary, indicates the historical record events of instability characterized by MAR overcoming lower than 6% (Appendix 1-B). Italic and bold were used to indicate meteorological events overcoming the 6% threshold, but not generating hydrogeological instability events according to the analysed historical archives and they sometimes correspond to disturb in, at least, 1 site. The oblique bars indicate the unavailability of data for the event for a source due to the temporal extension of the records at disposal.

Figure 1

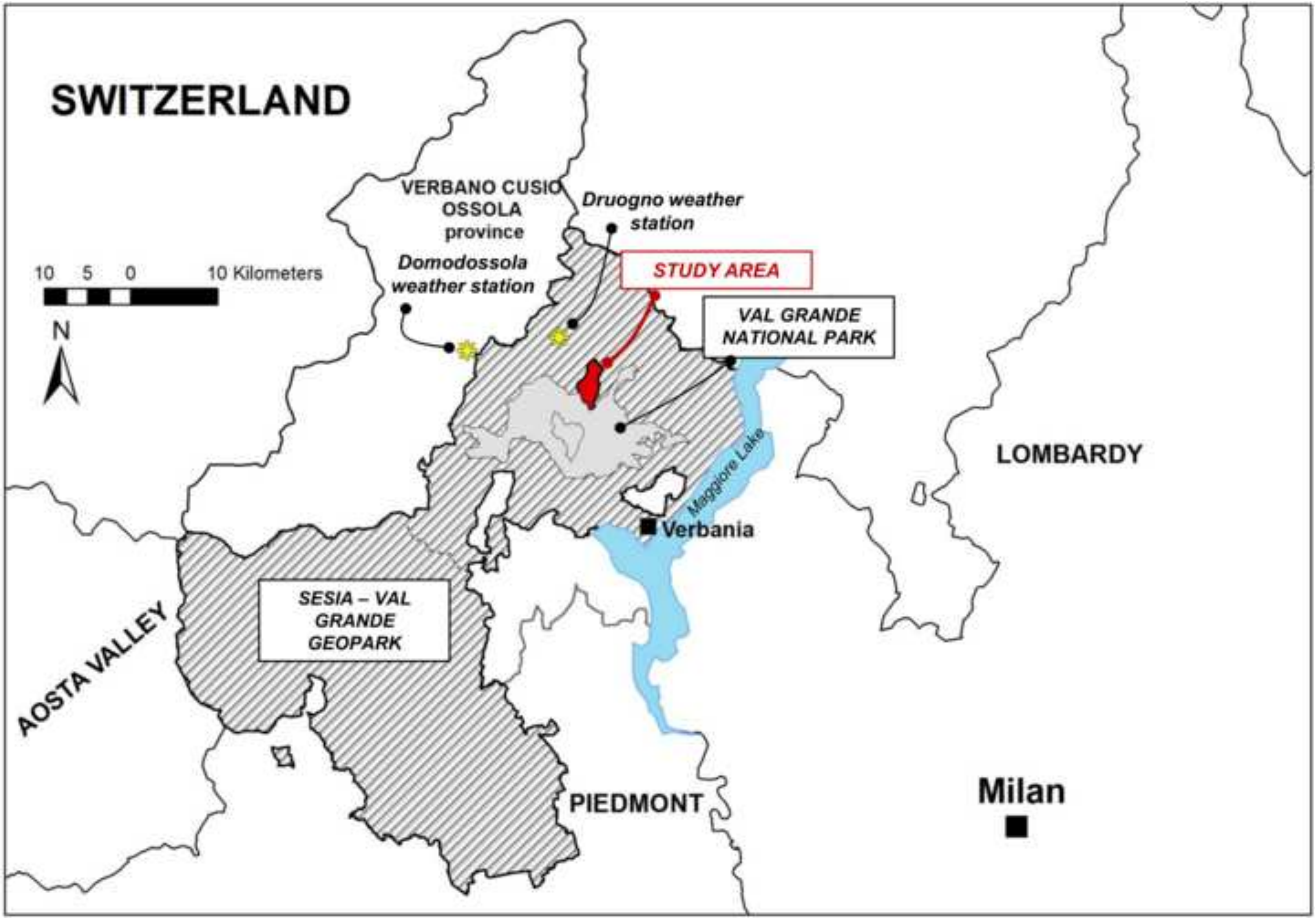
SWITZERLAND
10 5 0 10 Kilometers
N
VERBANO CUSIO OSSOLA province
Druogno weather station
Domodossola weather station
STUDY AREA
VAL GRANDE NATIONAL PARK
Maggiore Lake
Verbania
LOMBARDY
SESIA – VAL GRANDE GEOPARK
AOSTA VALLEY
PIEDMONT
Milan

Figure 2

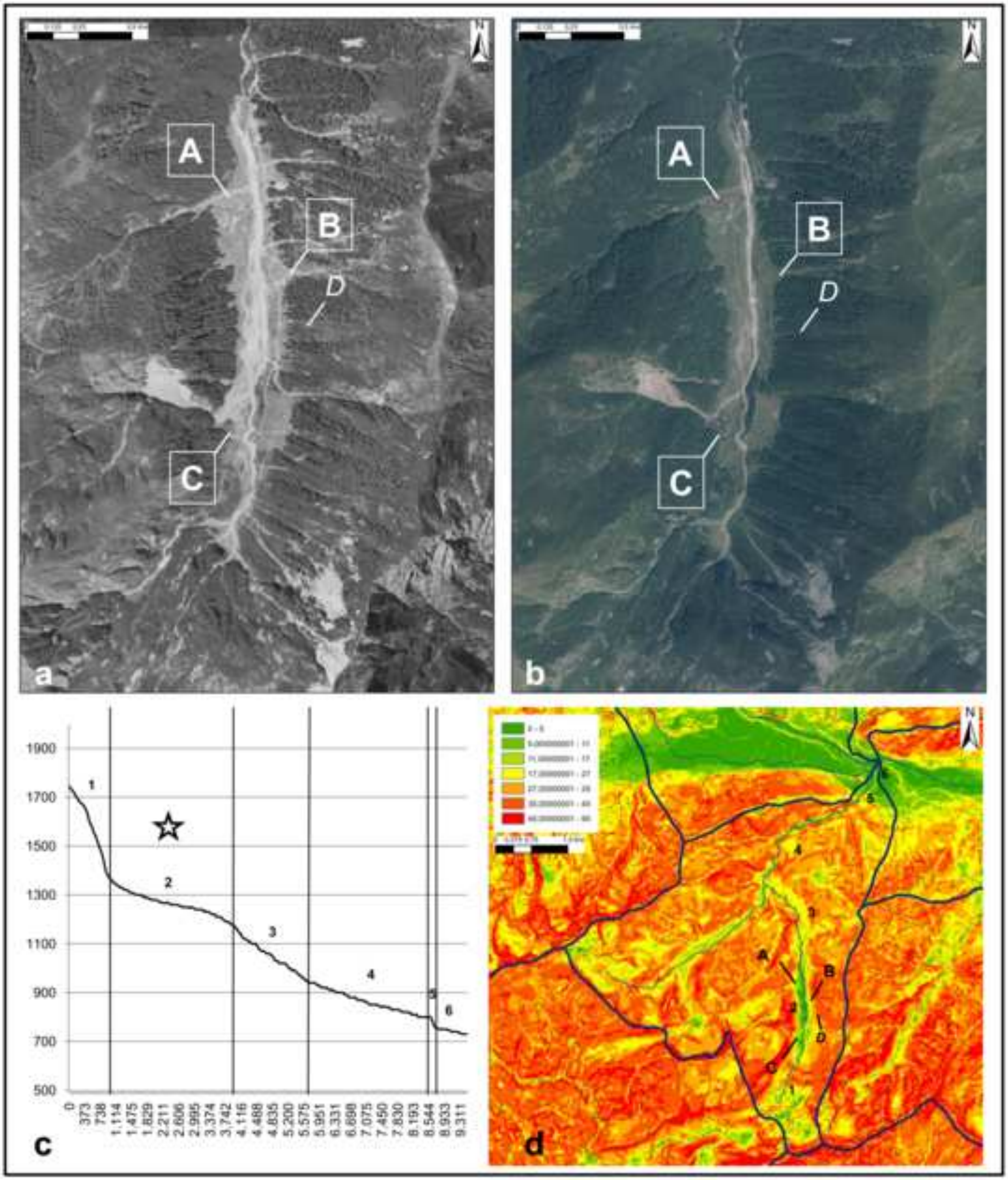
A
B
C
D
a
b
1900
1700
1500
1300
1100
900
700
500
0
373
738
1.114
1.475
1.829
2.211
2.606
2.995
3.374
3.742
4.116
4.488
4.835
5.200
5.575
5.951
6.331
6.698
7.075
7.450
7.830
8.193
8.544
8.933
9.311
1
2
3
4
5
6
☆
c
d

Figure_03_R1

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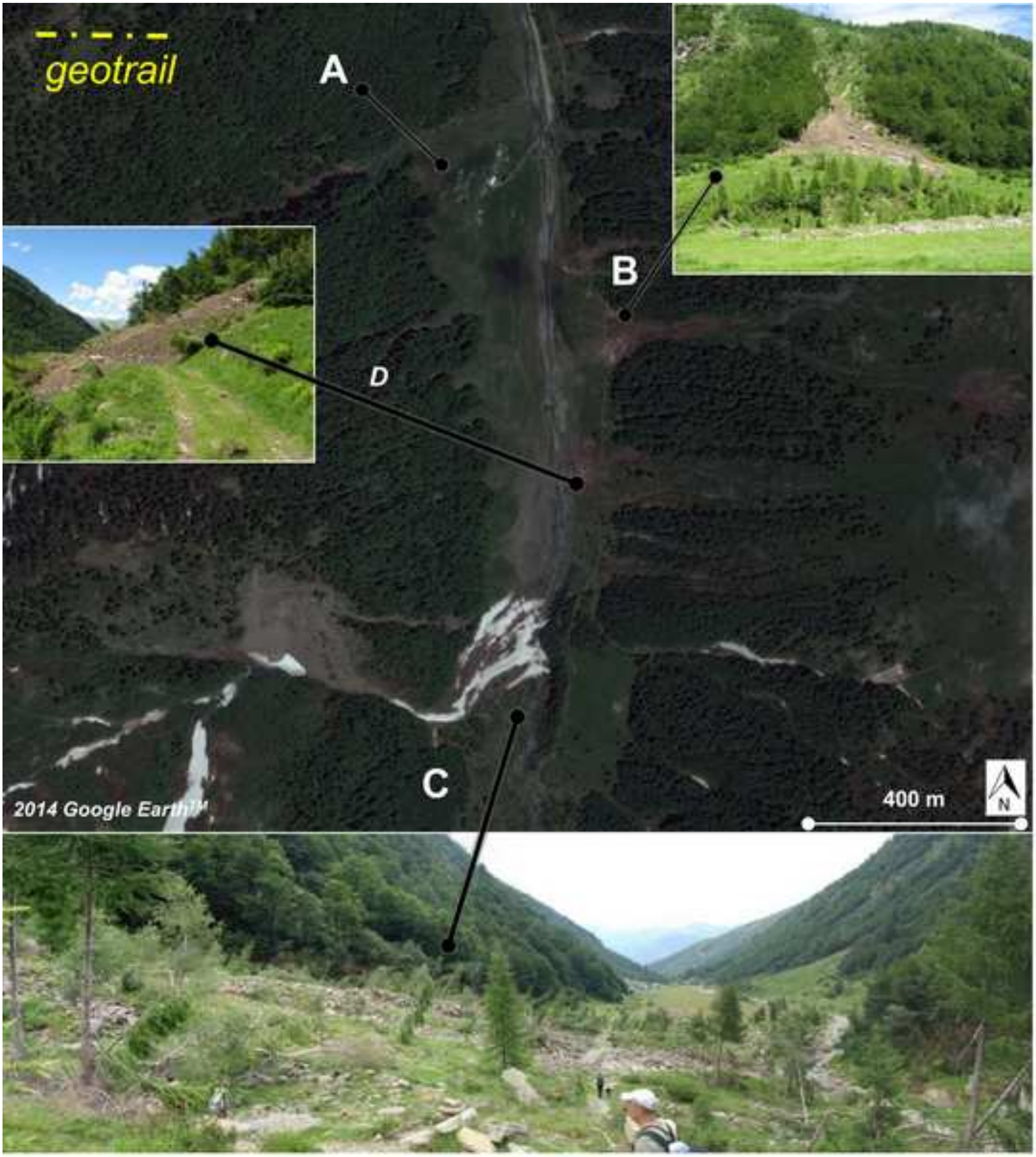

Figure_04_R2

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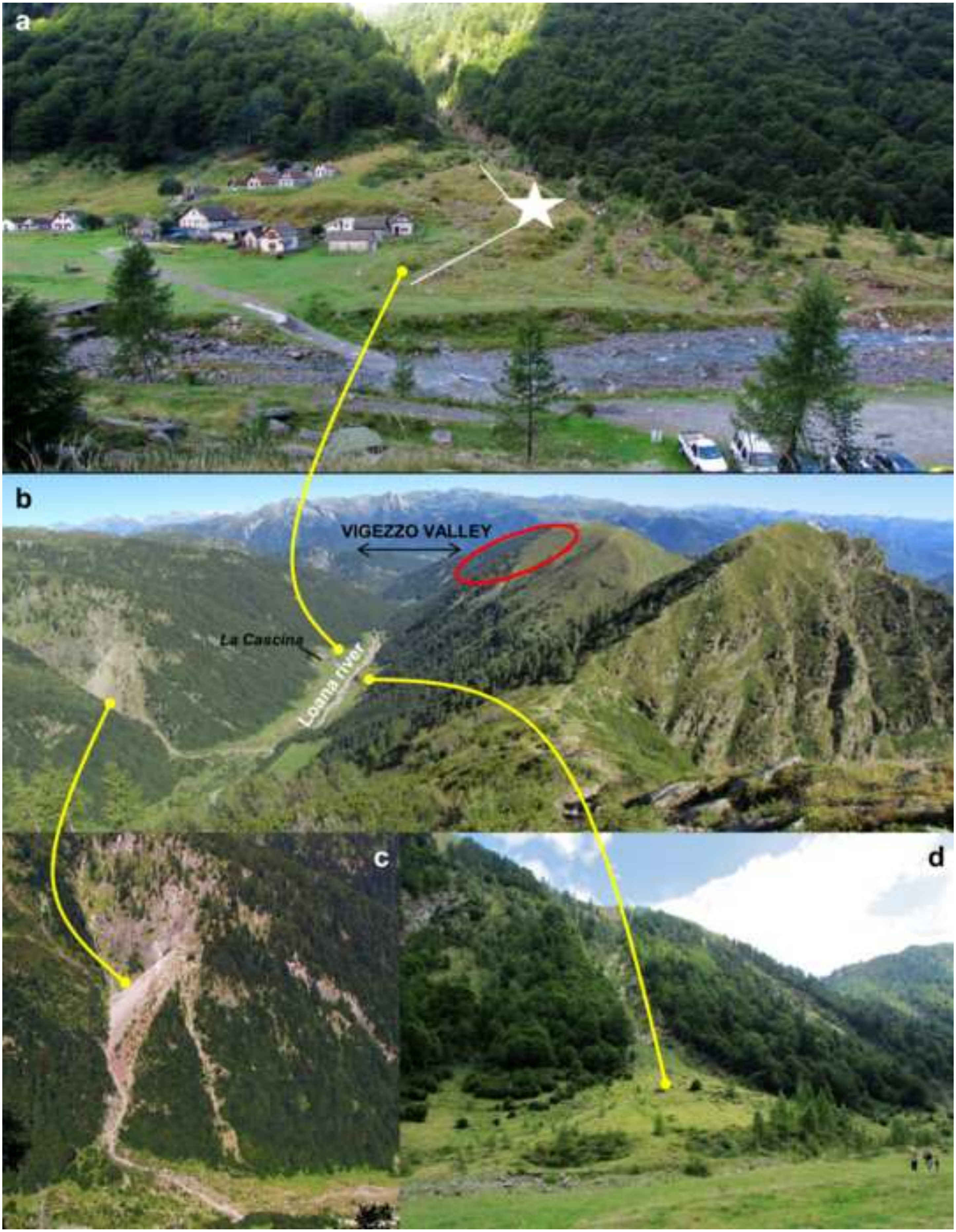


Figure_05_R2

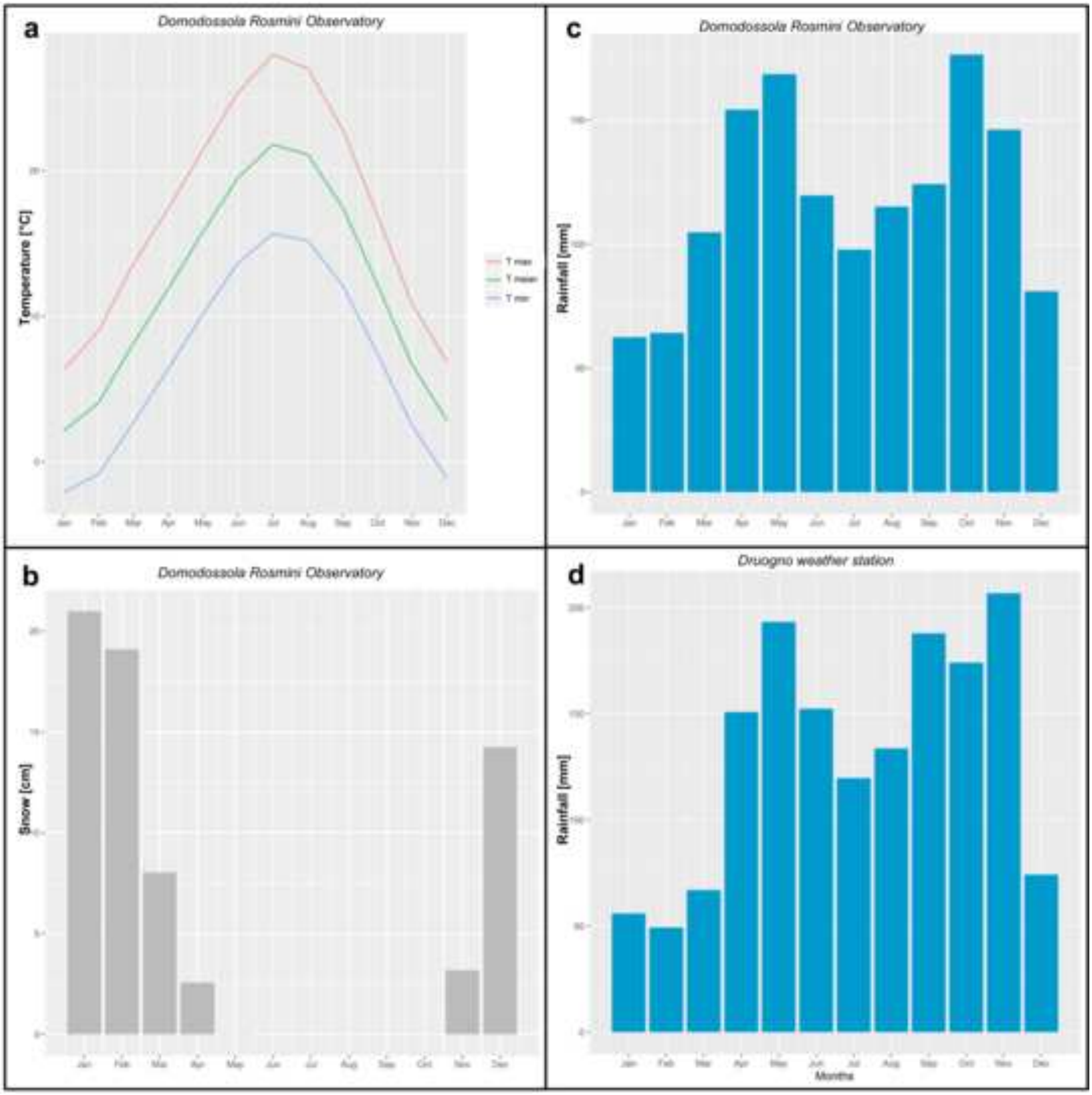

a
Domodossola Rosmini Observatory
Temperature [°C]
20
10
0
T max
T mean
T min
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
b
Domodossola Rosmini Observatory
Snow [cm]
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
c
Domodossola Rosmini Observatory
Rainfall [mm]
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
d
Druogno weather station
Rainfall [mm]
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months

Figure_06_R1

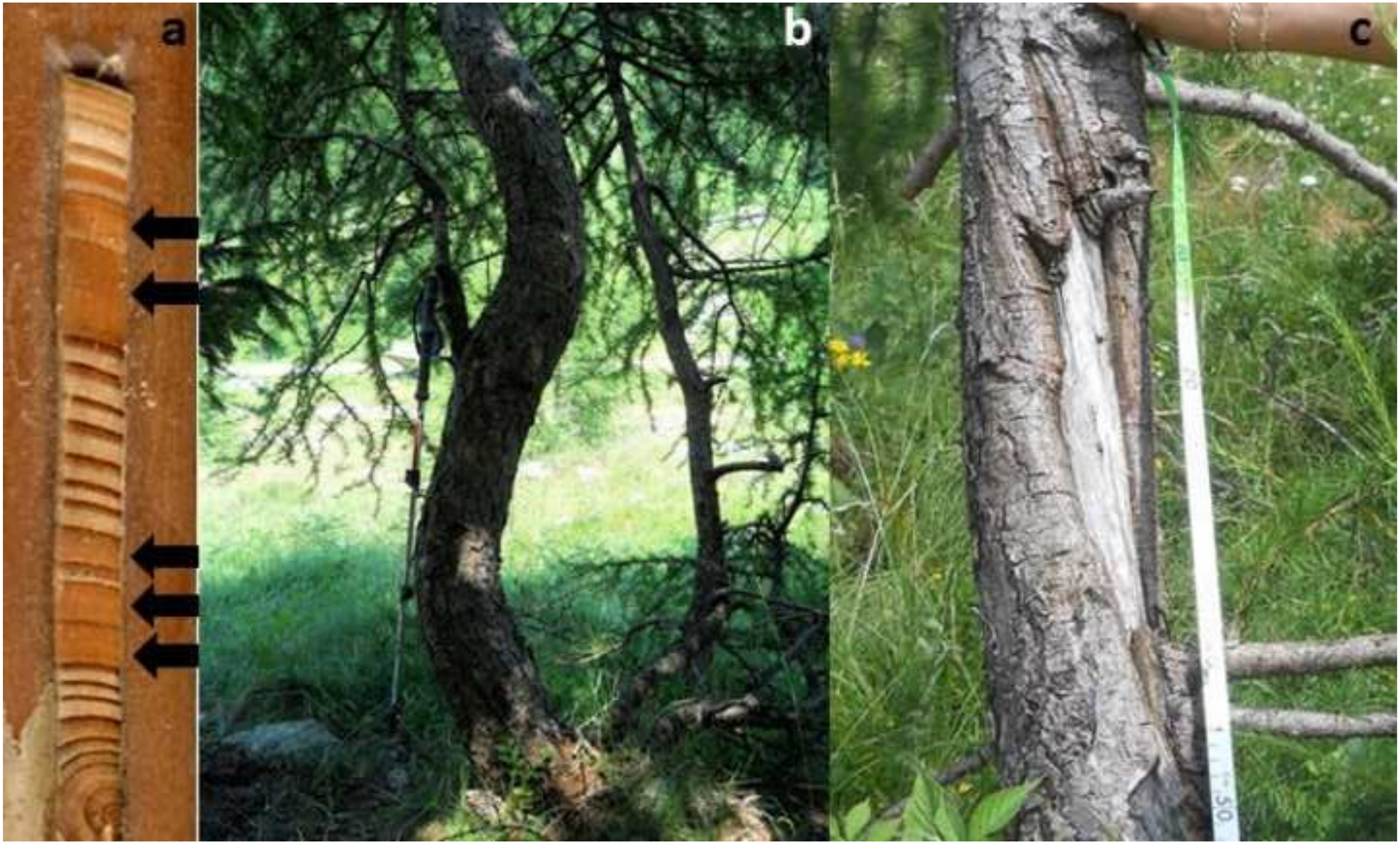


Figure 7

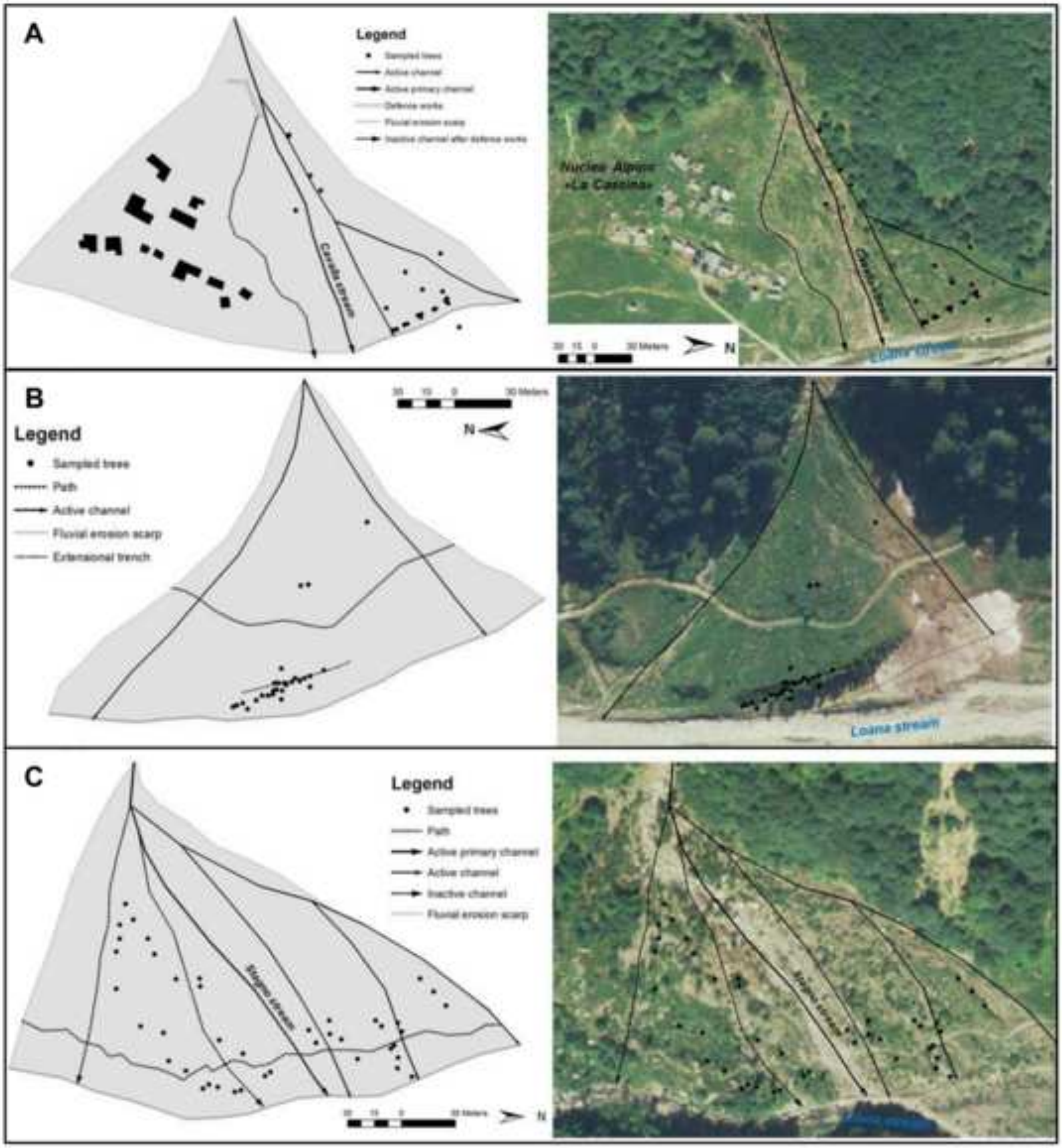
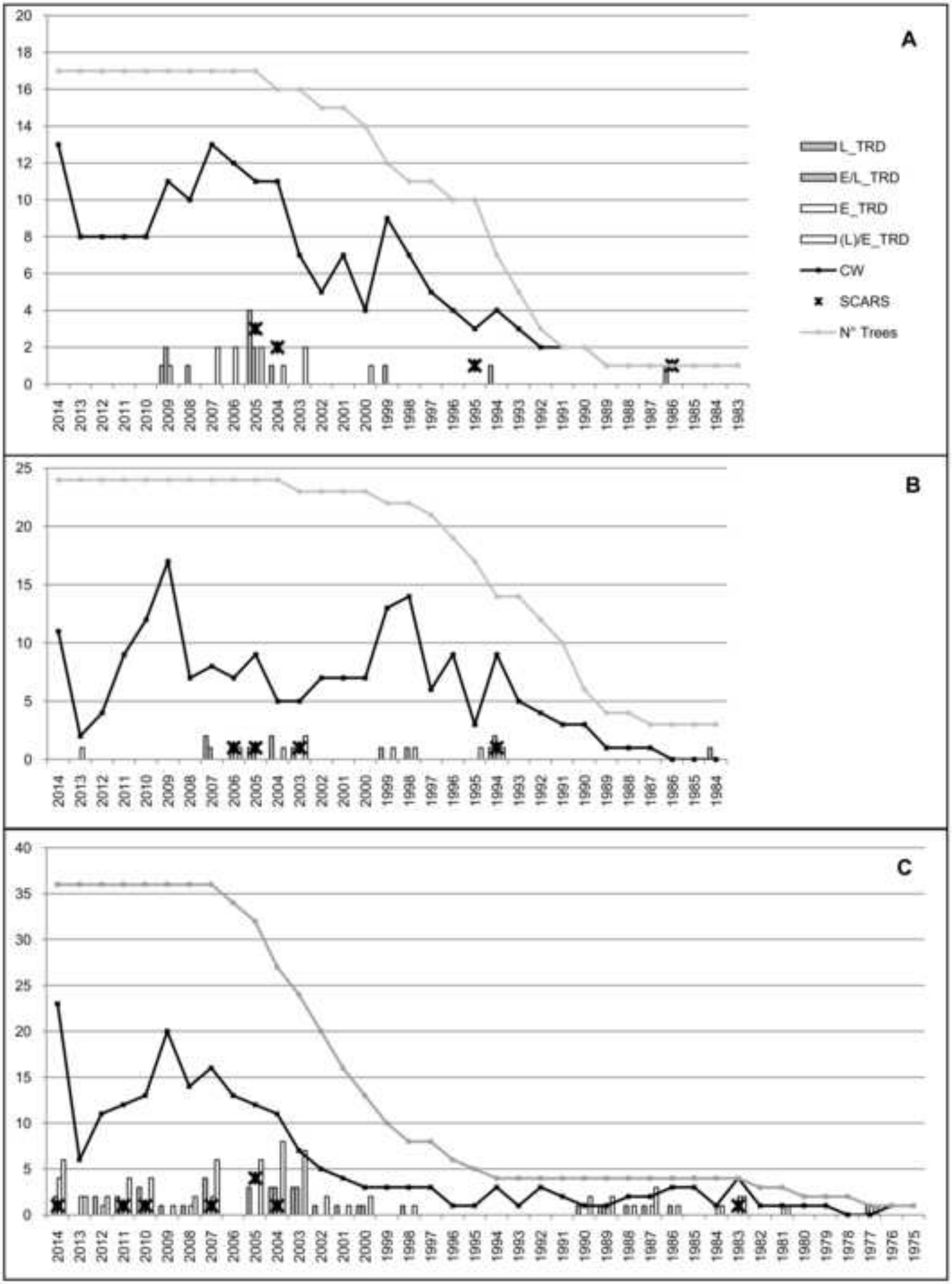

A
Legend
● Sampled trees
Active channel
Active primary channel
Defence works
Fluvial erosion scarp
Inactive channel after defence works
Cerasia stream
Nucleo Alpino «La Cascina»
30 15 0 30 Meters
N
Loana stream
B
Legend
● Sampled trees
Path
Active channel
Fluvial erosion scarp
Extensional trench
30 15 0 30 Meters
N
Loana stream
C
Legend
● Sampled trees
Path
Active primary channel
Active channel
Inactive channel
Fluvial erosion scarp
Stagno stream
30 15 0 30 Meters
N

Figure 8


A
B
C
0
2
4
6
8
10
12
14
16
18
20
25
30
35
40
L_TRD
E/L_TRD
E_TRD
(L)/E_TRD
CW
SCARS
N° Trees
2014
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
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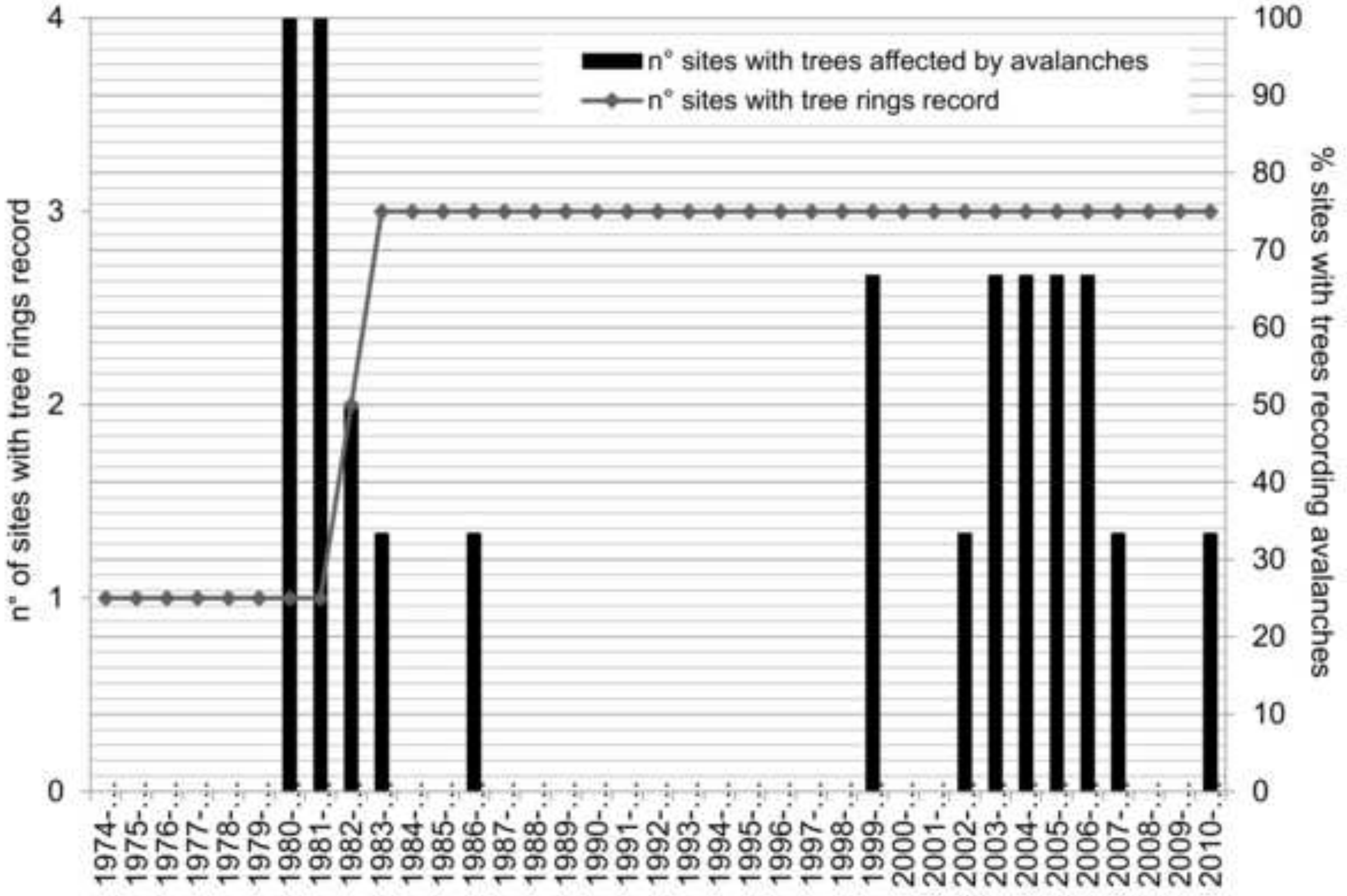
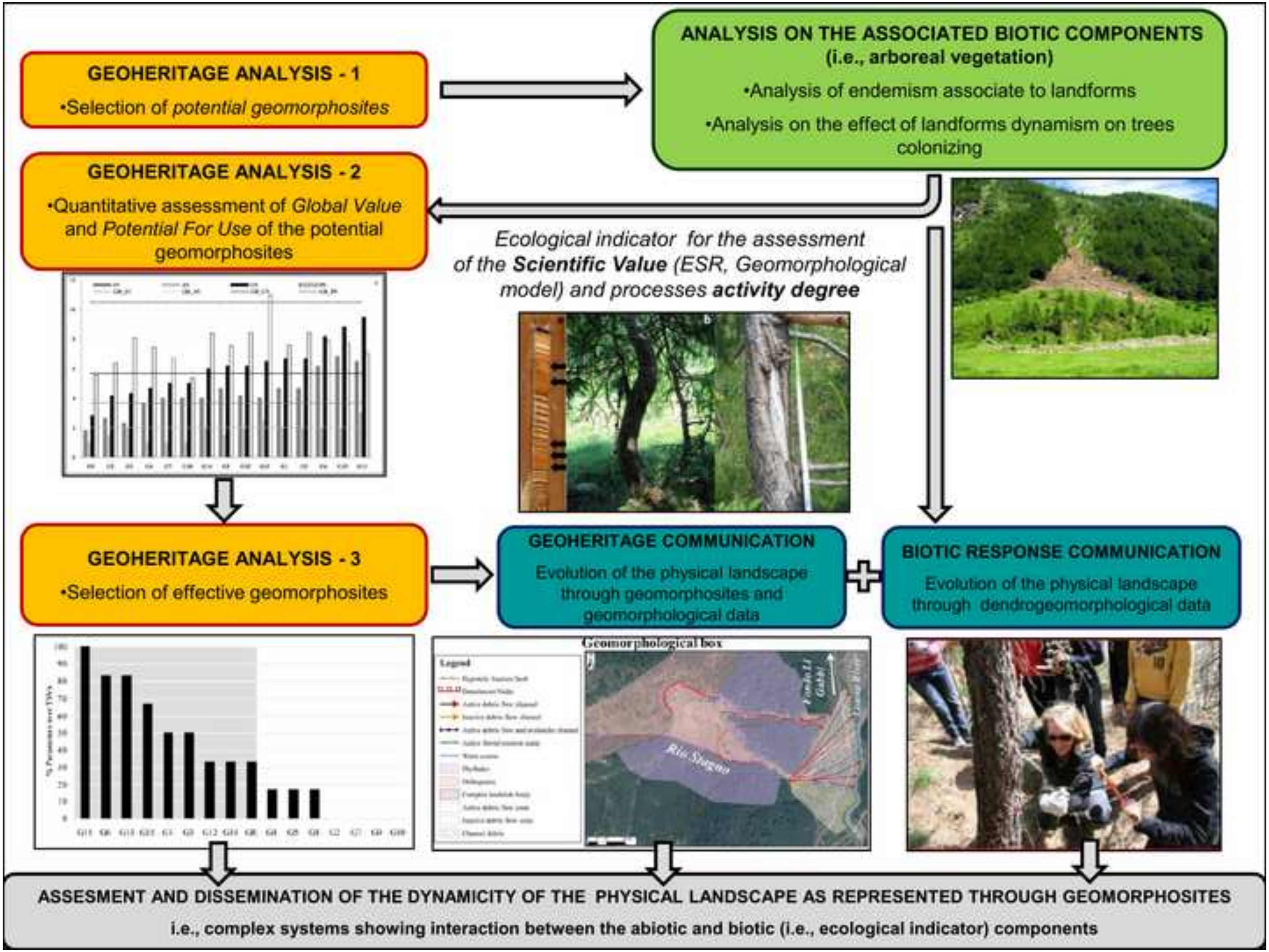
1977
1976
1975

Figure_09_R1



	A	B	C
Total n° of events	4	3	7
% recorded events	36.36	27.27	63.64

Figure_10_R1



GEOHERITAGE ANALYSIS - 1

•Selection of *potential geomorphosites*

ANALYSIS ON THE ASSOCIATED BIOTIC COMPONENTS (i.e., arboreal vegetation)

•Analysis of endemism associate to landforms

•Analysis on the effect of landforms dynamism on trees colonizing

GEOHERITAGE ANALYSIS - 2

•Quantitative assessment of *Global Value* and *Potential For Use* of the potential geomorphosites

Ecological indicator for the assessment of the ***Scientific Value*** *(ESR, Geomorphological model) and processes* ***activity degree***

GEOHERITAGE ANALYSIS - 3

•Selection of effective geomorphosites

GEOHERITAGE COMMUNICATION

Evolution of the physical landscape through geomorphosites and geomorphological data

BIOTIC RESPONSE COMMUNICATION

Evolution of the physical landscape through dendrogeomorphological data

ASSESMENT AND DISSEMINATION OF THE DYNAMICITY OF THE PHYSICAL LANDSCAPE AS REPRESENTED THROUGH GEOMORPHOSITES

i.e., complex systems showing interaction between the abiotic and biotic (i.e., ecological indicator) components

Appendix_1_R2

Interactive Map file (.kml or .kmz)

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