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THE INFLUENCE OF GEOMORPHOLOGICAL PROCESSES ON THE TREELINE POSITION IN UPPER VALTELLINA (CENTRAL ITALIAN ALPS)

ABSTRACT: MASSEROLI A., LEONELLI G., BOLLATI I., TROMBINO L. & PELFINI M., *The influence of geomorphological processes on the treeline position in Upper Valtellina (Central Italian Alps).* (IT ISSN 0391-9839, 2016)

Although altitudinal treelines are generally influenced by climatic conditions, geomorphological processes and human activities can locally limit the treeline position, conditioning its altitude and dynamics. In fact, in mountain regions, tree establishment and growth at the highest altitudes may be greatly affected by geomorphological processes and/or human impacts.

This study spatially and statistically examines the role of geomorphological processes and related landforms on the treeline position in Upper Valtellina (Central Italian Alps) through the observation of orthophotos and thematic maps by means of GIS software. Landforms located at the treeline boundary have been grouped according to their genetic origin into three classes: i) those shaped by running and/or channelized water, ii) those due to gravitational processes and iii) those due to snow and ice processes. For each tree belonging to the analysed treelines, the main active geomorphological process and the distance from the timberline (treeline ecotone width) have been associated.

The gravitational processes are the most widespread along the treeline ecotone in Upper Valtellina. They represent the most significant geomorphological limiting factor for the treeline altitude, especially where deposits due to gravitational processes merge (e.g., merging talus cones and talus slope; treeline mean elevation: 2300 m a.s.l.). Gravitational processes, documented by the related active landforms, are also the most destructive of the treeline ecotone, reducing its width (mean width: 83 m) and inducing the overlap of treeline and timberline. In contrast, periglacial processes exert much less influence on the treeline position (mean elevation: 2419 m a.s.l.).

KEY WORDS: Treeline; Geomorphological processes; Landforms; Valtellina; Italian Alps; Aerial photo interpretation.

RIASSUNTO: MASSEROLI A., LEONELLI G., BOLLATI I., TROMBINO L. & PELFINI M., *L'influenza dei processi geomorfologici sulla posizione della treeline in Alta Valtellina (Alpi Centrali Italiane).* (IT ISSN 0391-9839, 2016)

Il limite degli alberi (treeline) è considerato un buon indicatore del cambiamento climatico; la sua posizione e dinamica altitudinale possono tuttavia essere influenzate anche da fattori geomorfologici e dall'impatto antropico. Ad alta quota, infatti, i processi geomorfologici possono limitare la colonizzazione arborea e la crescita degli alberi.

In questo studio è stato analizzato spazialmente e statisticamente il ruolo dei processi geomorfologici delle forme associate sulla posizione della treeline in Alta Valtellina (Alpi Centrali Italiane). L'analisi è stata effettuata, mediante l'osservazione di ortofoto e mappe tematiche, con l'utilizzo di un software GIS e ha interessato solo le treeline fortemente condizionate dai processi geomorfologici attivi. Le forme individuate nell'ecotono della treeline sono state raggruppate, in base alla loro origine, in tre classi: i) forme legate all'azione delle acque dilavanti e incanalate, ii) forme legate all'azione della gravità e iii) forme legate all'azione del ghiaccio e della neve. Ad ogni albero appartenente alla treeline, è stato associato il processo che principalmente ne influenza la posizione. È stata altresì calcolata la differenza altitudinale tra treeline e timberline (ampiezza dell'ecotono della treeline).

Tra le forme prese in esame quelle legate ai processi gravitativi sono le più diffuse nell'ecotono della treeline. La presenza di processi gravitativi determina, inoltre, un maggiore abbassamento in quota della treeline, in particolare, dove questi danno luogo a depositi coalescenti (quota media della treeline 2300 m s.l.m.). Anche l'ampiezza dell'ecotono della treeline è maggiormente ridotta laddove si rinvengono depositi coalescenti dovuti all'azione di processi gravitativi (ampiezza media dell'ecotono pari a 83 m). Questi ultimi risultano essere i processi con effetto maggiormente distruttivo sull'ecotono della treeline, portando in alcuni casi anche alla sovrapposizione della treeline con la timberline. I processi periglaciali sembrano, invece, essere i meno influenti sulla posizione della treeline (quota media treeline 2419 m s.l.m.).

TERMINI CHIAVE: Treeline; Processi geomorfologici; Forme del paesaggio; Valtellina; Alpi Italiane; Fotointerpretazione.

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INTRODUCTION

The treeline ecotone, defined as the transition zone in mountain vegetation between the closed forest (timberline) and the alpine grasslands (Körner, 1999), is one of the most distinctive features of the mountain environments and it is widely considered a climatic boundary.

Treelines may be defined by considering the trees more than 2-3 m tall growing at the highest altitude (treeline elevation) (Körner, 2003; 2012; Tinner & Theurillat, 2003).

Treeline fluctuations may be considered for the assessment of past and ongoing climatic and environmental changes. Upward and downward shifts in treeline in response to climate variability during the Holocene were highlighted by many studies (Tinner & Theurillat, 2003; Scapozza & *alii*, 2010). Moreover, a current upward treeline shift, caused by the ongoing climate change, has been observed in the Alps (e.g., Gehrig-Fasel & *alii*, 2007; Caccianiga & *alii*, 2008, Leonelli & *alii*, 2016; 2011) and in many parts of the globe (Kullman, 2002; Roush, 2009; Shiyatov & *alii*, 2007; Harsh & *alii*, 2009).

Although the ecological dynamics of the alpine treeline ecotone is mainly influenced by climate, especially by soil temperature (Körner & Paulsen, 2004), climatic parameters are not the only factors that influence the treeline position (Malanson & *alii*, 2007). In fact, the treeline altitude may be locally influenced by environmental factors, disturbances, and human activities (Zald & *alii*, 2012; Holtmeier & Broll, 2007; Motta & Garbarino, 2003; Chauchard & *alii*, 2007; Leonelli & *alii*, 2009).

At high altitude, geomorphic processes play a key role in conditioning treeline position (Leonelli & *alii*, 2011; Holtmeier & Broll, 2012; Walsh & *alii*, 1994). Tree germination and growth are affected by local topography (e.g., slope features, slope steepness, and bare rock walls) and by active surface processes shaping and reworking landforms, especially those due to gravitational processes, such as debris cones, talus, debris flow fans, avalanche fans, etc. (Holtmeier & Broll, 2005). Moreover, water-driven erosional processes, such as rain wash, action of running water, etc., that form gullies and eroded surfaces as well as spectacular landforms such as calanchi and earth pyramids (Bollati & *alii*, 2012; 2016) can play an ecological supportive role by conditioning the other components of the ecosystem (e.g., vegetation) via effects on tree growth and vegetation dynamics.

Mass wasting is one of the most common, widespread, and complex processes acting in the Alpine environment (Haeberli & *alii*, 1997). Seasonal debris falls, debris flows, landslides, and other events can, in conjunction with the effects of avalanches, generate a diffuse disturbance in the treeline dynamics. Indeed, treeline can be lowered in elevation well below the climate-controlled alpine treeline altitude (Butler & *alii*, 2009; Leonelli & *alii* 2009; 2016). Nevertheless, at a local scale, geomorphological depositional processes and landforms can create favourable site conditions where tree seedlings may establish and survive (Butler & *alii*, 2007; Virtanen & *alii*, 2010; Resler, 2006).

Finally, the geomorphic processes are fundamental to understanding the distribution of trees. Moreover, the upward shift in the treeline under the ongoing temperature warming will be severely limited by the availability of sites with adequate geomorphic/topographic characteristics (Macias Fauria & Johnson, 2013).

The main aim of this study is to spatially and statistically analyse the influence of geomorphological processes and landforms on the treeline position in Upper Valtellina (Central Italian Alps). Specifically, the goals are as follows: i) to identify, analyse and quantify the active and inactive surface processes acting on the treeline ecotone, ii) to identify the geomorphological processes that are most effective in lowering the current treeline position compared to the treeline altitude in geomorphologically undisturbed environments, iii) to analyse the influence of the different geomorphological processes on the treeline ecotone width, and iv) to determine the most frequent geomorphological processes and landforms influencing the treeline and timberline altitudes.

STUDY AREA

This research has been carried out in the Central Italian Alps (fig. 1), specifically in Upper Valtellina (Ortles - Cevedale Group - Sondrio Province).

Upper Valtellina is characterized by outcrops of several polymetamorphic crystalline rocks, such as marble- and parasinite-bearing phyllites (e.g., Bormio Phyllites) and paragneissic units with augen gneisses and amphibolites (Cavallin & *alii*, 1997). In the southern portion of Upper Valtellina, granitic and granodioritic bodies crop out, and stratified gabbroic intrusions are present around Sondalo village. In the northernmost part of Upper Valtellina, the substrate is characterized by a complex system of thick carbonate successions (Montrasio & *alii*, 1990; Cavallin & *alii*, 1997).

The complex morphology of Upper Valtellina is the result of both the lithological and structural aspects of the region, as well as the changes in type and/or frequency and intensity of geomorphological processes due to climatic changes. Glacial processes play a preeminent role, resulting in well-preserved typical landforms (e.g., U-shaped valleys, troughs, cirques, and moraine ridges) (Bellotti & *alii*, 1995) and contributing to the local geoheritage (Pelfini & Gobbi 2005; Garavaglia & *alii*, 2010). Due to the high altitude, the study area is characterized by periglacial processes and landforms, such as rock glaciers, protalus ramparts, and others (Scotti & *alii*, 2013). Moreover, avalanche channels and cones are also common. The action of freeze-thaw cycles and the effects of gravity have contributed to the formation of debris slopes at the base of the cliffs (Bellotti & *alii*, 1995). Gravity-related processes and landforms (e.g., talus cones, debris fans, debris flows and landslide deposits) are common in the study area, which is characterized by high-relief areas and high-elevation peaks, especially in the eastern part (i.e., Ortles-Cevedale Group; Pozzi & *alii*, 1990). The morphogenetic role of water runoff is also locally active: many gullies related to concentrated runoff are present, and they can be attributed to the current erosive action of running water. Evidence of sheet erosion is also common (Bellotti & *alii*, 1995).

The climate of Upper Valtellina is alpine continental, with a typical high annual temperature range (minimum temperatures occur in January, and maximum tempera-

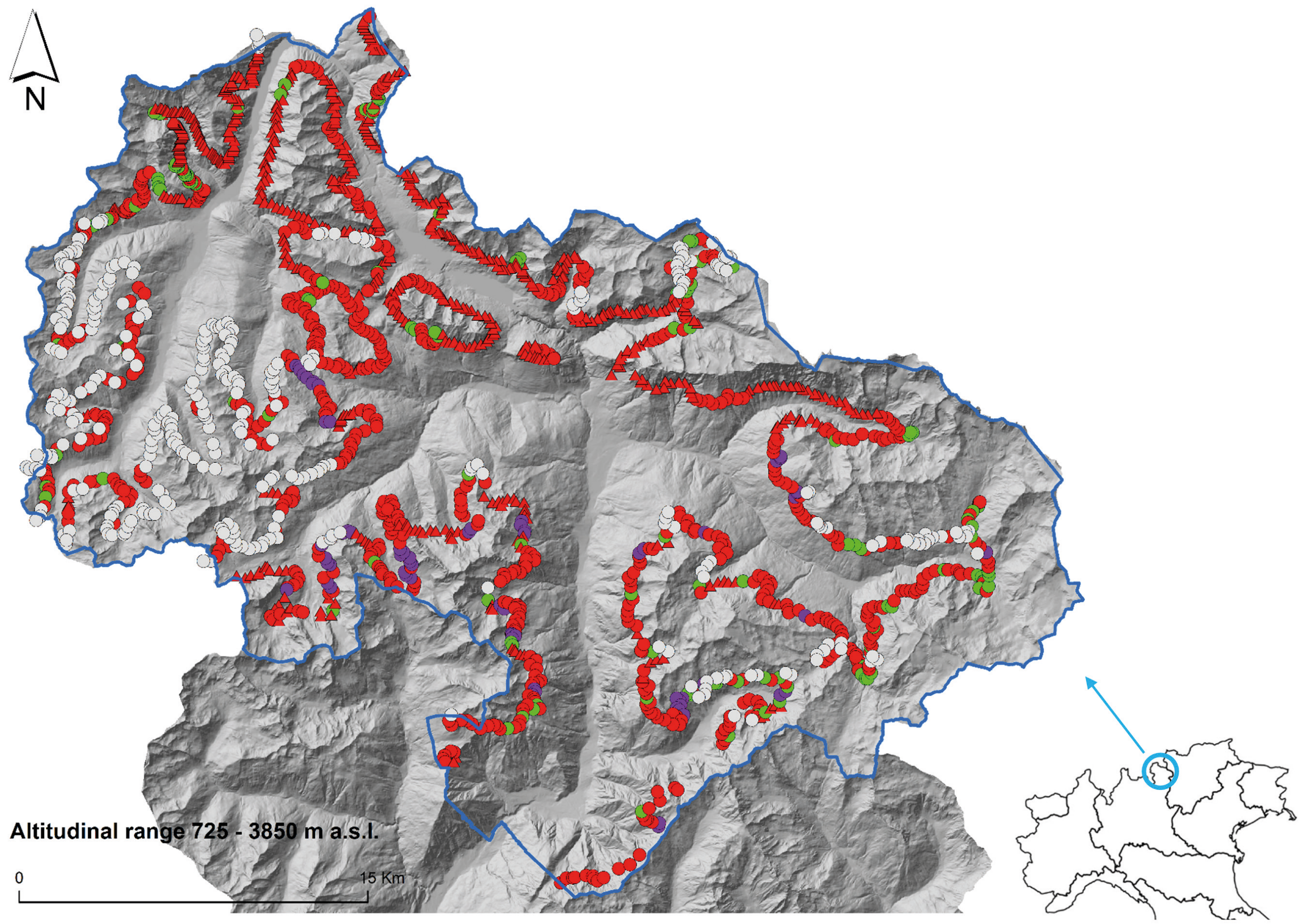

FIG. 1 - Treeline position in the Upper Valtellina region, differentiated according to the main processes influencing its position: surface areas affected by running and/or channelized water processes (green dots); isolated deposits due to gravitational processes (red dots); merging deposits due to gravitational processes (red triangles); and periglacial processes (violet dots). The grey dots depict the treelines limited by human impacts or the climatic treelines. Modified from Leonelli & alii, (2016).

tures occur in July). Rainfall is scarce in the valley bottom, with an annual average between 700 and 900 mm, which mainly falls during the summer (Nigrelli, 2008).

Swiss stone pine (*Pinus cembra* L.) and European larch (*Larix decidua* Mill.) dominate the Upper Valtellina forests. In the northeast (near Lake Cancano), *Pinus montana* Miller is the most common species and is joined by sporadic European larches and Swiss stone pines (Pelfini & *alii*, 2006). Forests of Norway spruce (*Picea abies* Karst.) occur near the bottoms of valleys, at lower elevations than the European larch and Swiss stone pine forests (ERSAF, 2012).

METHODS

Treeline position and elevation were estimated on orthophotos (WMS service) by means of the Quantum GIS Software for the whole administrative area of the Comunità Montana Alta Valtellina (896 km^2) in a previous study (Leonelli & *alii*, 2016), and the environmental factors controlling the upward/downward shift in the treeline were identified, distinguishing between geomorphological constraints, climate and human impacts.

In this study, trees belonging to the "treelines with geomorphological constraints" defined in Leonelli & *alii* (2016) have been analysed with new goals. For each tree of this geomorphologically constrained group, the geomorphological process that prevents the upward treeline shift has been determined using a combination of three different approaches: i) indirect observation of geomorphic evidence corresponding to the detected trees at the treeline using orthophotos for the years 2006 and 2007 (http://www.pcn.minambiente.it/GN/_WMS service); ii) analysis of the thematic maps available on the Lombardy regional geoportal (http://www.geoportale.regione.lombardia.it/; tab. 1); and iii) comparison with previously published geomorphological maps related to Upper Valtellina (Pozzi & *alii*, 1990; Bellotti & *alii*, 1995).

To disentangle the different effects of the various geomorphological processes on the treeline altitude and on the ecotone width, erosional and depositional landforms located at the treeline boundary have been grouped according to their predominant genetic process. Specifically, they have been grouped into three classes: landforms mainly due to running and/or channelized water (e.g., due to sheet

TABLE 1 - Layers used for the characterization of geomorphologically constrained treelines and for the association of each geomorphologically constrained treeline tree with the process limiting its position. For each layer, the original shapefile name, the group where the layer is located in the regional geoportal, the year of the last update and the URL are specified.

Shapefile name	Group of layers	Year	URL
Rock scree (Accumuli di frana)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Highly unstable areas (Aree ad elevata instabilità)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Areas exposed to channeled water erosion (Aree con erosione delle acque incanalate)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Areas exposed to water runoff and surface erosion (Aree di dilavamento e di erosione superficiale)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Geomorphic areas (Aree geomorfiche)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Potentially unstable areas (Aree potenzialmente instabili)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Alluvial fan (Conoidi di deiezione)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Scree slope and/or talus cone(Depositi detritici orientati)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Surface deposits (Depositi superficiali)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Punctual geomorphological features (Elementi geomorfologici puntuali)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Punctual elements of gravity and water runoff (Elementi puntiformi di gravità e dilavamento)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Fluvio-glacial erosion /melt water channel (Erosione incanalata scaricatore fluvioglaciale)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Glaciers and snowfields (Ghiacciai e nevai)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Landslide niches (Nicchie di frana)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Protalus rampart and Rocky crest-line (Nivomorena e cresta)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Rock glacier (Rock glacier)	Geoambientale	01/01/1987	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Landslide areas (Aree franose)	GeoIFFI	05/02/2004	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Areas subjected to rock fall, landslides, collapses (Aree soggette a crolli, franosità, sprofondamenti)	GeoIFFI	05/02/2004	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Alluvial fans (Conoidi)	GeoIFFI	05/02/2004	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Deep-seated gravitational slope deformation (Deformazioni gravitative profonde di versante)	GeoIFFI	05/02/2004	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Linear landslides (Frane lineari)	GeoIFFI	05/02/2004	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Avalanche sites by photo-interpretation (Siti valanghivi da fotointerpretazione)	Sistema Informativo Regionale Valanghe	13/05/2011	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Avalanche sites by survey (Siti valanghivi da rilevamento)	Sistema Informativo Regionale Valanghe	13/05/2011	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Mountain community 2012 (Comunità montane 2012)	Limiti amministrativi 2012 agg.DBT/PGT	05/10/2012	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Glaciers 2013 (Ghiacciai 2013)	Ghiacciai della Lombardia	16/07/2013	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Isoipse (Curva di livello 10000 CT10)	Carta Tecnica Regionale 10000 vettoriale CT10	01/07/2006	http://www.cartografia.regione.lombardia.it/rlregisdownload/
Hydrographic network (Rete idrografica 10000 CT10)	Carta Tecnica Regionale 10000 vettoriale CT10	01/07/2006	http://www.cartografia.regione.lombardia.it/rlregisdownload/
DTM (Digital terrain model)	DTM	14/01/2014	http://www.geoportale.regione.lombardia.it/
2006 Color Ortophotos (Ortofoto a colori anno 2006 con relative date del volo)	WMS service	2007	http://www.pcn.minambiente.it/GN/ to_colore_06.map)

TABLE 2 - Classification adopted for the different processes and related landforms limiting the position of treeline trees.

Type of landform	Agents	Landforms	Classes	Classes of landforms used for the analysis
Erosional	Gravity/Water/Snow	Avalanches channels, tracks	Landforms due to a combination of avalanches processes and running and/or channelized water	Gullies
Erosional	Water	Gullies	Landforms due to running and/or channelized water	Gullies
Erosional	Water	Rills		Rills
Depositional	Water	Alluvial fans		Alluvial fans
Depositional	Gravity/Water	Debris flow fans	Landforms due to gravity (mass movements)	Gravity deposits (isolated or merging)
Depositional	Gravity	Scree slopes, talus slopes, debris cones		
Depositional	Gravity	Deep-seated gravitational slope deformation		
Depositional	Gravity	Rock screes		
Depositional	Interstitial Ice	Rock glaciers	Cryogenic landforms	Rock glaciers

erosion, rill erosion or gully erosion), landforms mainly due to gravitational processes (e.g., mass movements, such as rock falls, landslides, debris flows, etc.) and landforms mainly due to the action of snow and ice (e.g., related to glacial and periglacial processes and avalanches; tab. 2).

The selected landforms related to running and/or channelized water include erosional forms, such as rills and gullies, and deposits, such as alluvial fans and/or mixed alluvial cones. These type of landforms have been analysed separately (tab. 2).

In the study area, avalanches are a very common phenomena that locally overlap other processes and contribute to shaping the landscape (e.g., debris cones are actually composite cones sensu Baroni & *alii*, 2007). The two layers of the Lombardy Region (Avalanche sites by photo-interpretation and by survey; tab. 1) cover about the entire treeline ecotone. Given the widespread presence of this process throughout the entire investigated area, avalanches have been considered background noise. However, where the impact of avalanches is coupled with the action of running water (i.e., rain wash erosion), the affected trees have been grouped with trees constrained by gully erosion.

Depositional landforms due to gravitational processes have been grouped into a unique category that includes scree slopes, rock screes, talus, debris cones and similar features. In this group, debris flow fans are also included for two reasons: i) gravity is the driving force of the process and ii) in most cases debris flows rework scree slopes, debris cones, and similar features. Moreover, gravity-related landforms have been classified as isolated landforms and merging landforms. This subdivision has been applied to better understand the role of gravitational processes on the treeline position and the different impacts that merging landforms have on the present treeline position.

Finally, among the glacial and periglacial landforms, only rock glaciers were taken into account because of the scale of observation. The widespread glacial deposits have not been taken into account because they have been reworked over time by other geomorphological processes (i.e., evolving passive landforms sensu Pelfini & Bollati, 2014).

The altitude of the treelines not disturbed by geomorphic processes, used as a comparison, refers to the altitude of climatic treeline in the study carried out in the same area by Leonelli & *alii* (2016).

To calculate the width of the treeline ecotone, the timberline position and elevation have been estimated by mapping approximately five trees (timberline trees) per km. In areas where the timberline was discontinuous or interrupted, the elevation of the nearest timberline has been considered.

The elevation value of each mapped tree at the timberline and at the treeline has been extracted from a 20-m DTM of the Lombardy Region (Regione Lombardia, 2014; tab. 1).

To evaluate whether the presence (distribution, spatial continuity, etc.) of genetically different landforms causes differences in the frequency distribution of the elevation of treeline trees (trees at the treeline), chi-square tests have been performed. The variable "elevation" has been transformed into analogous ordinal data with 10 interval classes (tab. 3). The tests have been carried out by comparing all the landforms and by comparing only different classes of landforms (tab. 5).

TABLE 3 - Class number and corresponding class intervals into which the elevation variable was subdivided.

Class	Elevation interval (m a.s.l.)
10	2551 – 2640
9	2501 – 2550
8	2451 – 2500
7	2401 – 2450
6	2351 – 2400
5	2301 – 2350
4	2251 – 2300
3	2201 – 2250
2	2151 – 2200
1	1730 – 2150

TABLE 4 - Mean elevation of the treeline trees limited by geomorphological factors and mean width of the treeline ecotone. The treeline trees are grouped according to the landforms modelled or built by the processes most effective in influencing the treeline position. Values (m a.s.l.) are reported with an error of ±1 standard deviation.

	Isolated gravity deposits	**Merging gravity deposits**	**Gullies**	**Rills**	**Alluvial fans**	**Rock Glaciers**
Treeline mean elevation	2389 ± 87	2300 ± 97	2376 ± 84	2438 ± 63	2311 ± 87	2419 ± 73
Treeline ecotone mean width	183 ± 104	83 ± 94	177 ± 116	229 ± 50	155 ± 86	231 ± 78

TABLE 5 - Values of chi-square tests obtained by analysing the association between the landforms due to different processes that limit the treeline position and the elevation.

	χ^2	**d.f.**	**P**	**χ^2 Critical values**
All the landforms	363	45	0,005	73
All the classes	52	18	0,005	37
Landforms due to running and/or channelized water	36	18	0,005	37
Merging and isolated gravity deposits	276	9	0,005	24

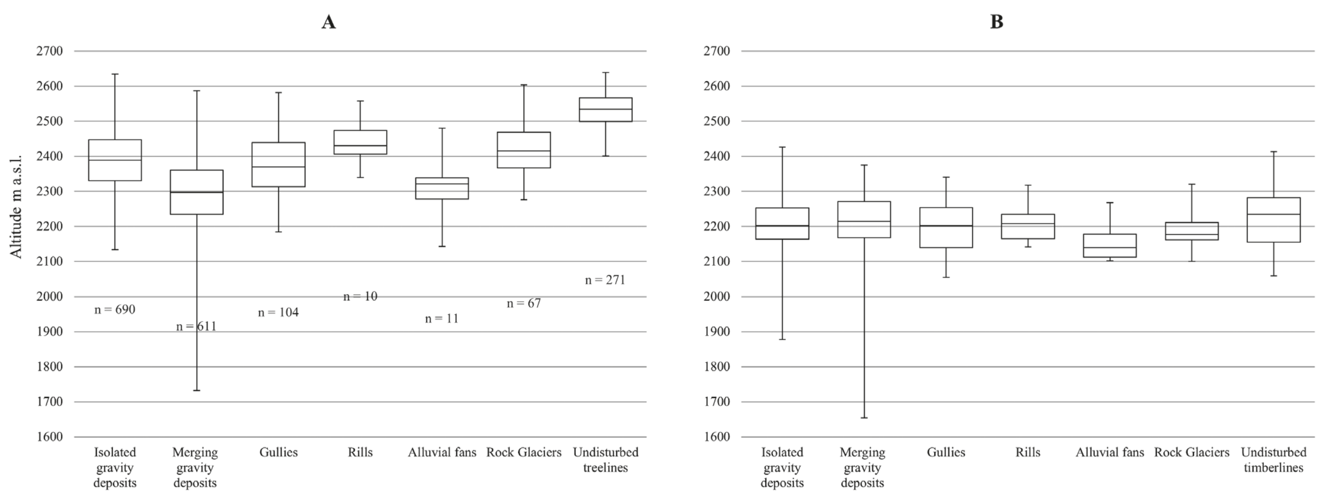

FIG. 2 - Distribution of treeline and timberline elevation. (A) Treeline trees were grouped in relation to the different landforms and geomorphological processes responsible for their position. The data on undisturbed treeline elevation was taken and modified from Leonelli & *alii*, (2016) (see "climatic treelines"). The whiskers of the boxplots correspond to minimum and maximum values. For each landform group, the number of affected trees is specified (n). (B) Timberline trees were grouped in relation to the different landforms and geomorphological processes affecting the treeline ecotone. The whiskers of the box plots correspond to minimum and maximum values.

RESULTS

Overall, the influence of geomorphological processes on the position of 1493 treeline trees with geomorphological constraints has been analysed in the study area. The data obtained after the analysis of the correspondence between tree location, morphogenetic landforms and active geomorphological processes indicate, in general, the treeline trees limited by geomorphological constraint are located at an average altitude lower than the treeline trees undisturbed by geomorphological processes (fig. 2A).

The results also highlight how different surface processes influence the treeline position and its altitudinal dynamics. Of the 1493 mapped trees belonging to the geomorphological treeline, 1301 (87%) are limited in their position by gravitational processes, 125 (8%) by processes due to running and/or channelized water and 67 (5%) by periglacial processes (fig. 1).

Gravitational processes are the most important processes influencing the dynamics of geomorphologically constrained treelines. Active depositional landforms, such as debris cones, talus slopes, scree slopes, and debris flow deposits, represent the main disturbances causing a lower altitude of a geomorphologically constrained treeline.

In particular, the presence of merging deposits due to gravitational processes (e.g., merging talus cones and wide scree slopes) heavily limits the treeline altitude (mean elevation: 2300 m a.s.l.; tab. 4), whereas the presence of isolated depositional landforms seems to be less influential (mean elevation: 2389 m a.s.l.; tab. 4).

Running water (e.g., rain wash and rill erosion) induces differentiated soil erosion, forming gullies and eroded slopes on which tree colonization may be very difficult. Rill erosion has less impact on the treeline (mean elevation: 2438 m a.s.l.) than gully erosion (mean elevation: 2376 m a.s.l.). Nevertheless, depositional landforms resulting from the action of water (i.e., small fans or mixed cones) are able to limit the treeline altitude (mean elevation: 2311 m a.s.l.; tab. 4).

Periglacial processes have a minor impact on the treeline. The presence of periglacial landforms, such as rock glaciers, has only a minor limiting factor (mean elevation: 2419 m a.s.l.; tab. 4).

Based on a comparison of the altitude of treeline trees in the analysed portion of Upper Valtellina and the "disturbing factors", it is evident that treeline trees limited by gravitational processes are the most widespread (fig. 1). The treelines limited by isolated landforms due to gravitational processes are mainly located in an elevation belt between 2133 m a.s.l. and 2634 m a.s.l.. Moreover, the treelines limited by merging deposits due to gravitational processes are mainly located in the northern portion of the study area and in an elevation belt between 1732 m a.s.l. and 2587 m a.s.l. (fig. 2A).

In addition, the treelines affected by running and/or channelized water processes, although less common, are distributed throughout the entire study area. Treelines limited by gullies and by alluvial cones are located between 2185 and 2582 m a.s.l. and between 2142 and 2480 m a.s.l., respectively. Rill erosion influences only a few treelines and was found in a small altitudinal range (between 2339 and 2558 m a.s.l.)

Rock glaciers affect the treelines located between 2276 and 2604 m a.s.l. mainly in the southern part of Upper Valtellina (fig. 2A).

Nevertheless, the altitude of the timberline trees limited by geomorphological processes is only slightly lower than that of the undisturbed timberline (fig. 2B). Moreover, the type of geomorphological processes does not seem to affect the position of the timberline; in fact, the median altitude value of the distribution of the timberline trees is approximately the same for all the different classes of landforms. However, the distribution of timberline trees affected by gravitational processes (and related geomorphic evidence) show greater low-altitude variability than that of the landforms associated with running and/or channelized water or cryogenic landforms (as evidenced in fig. 2B). Furthermore, only the altitude of timberlines associated with alluvial fans seems to be influenced by geomorphological processes.

These observations show that, in most cases, geomorphological processes control the position of the treeline altitude (they prevent potential upward shifts) but not the position of the timberline altitude. Moreover, the treeline ecotone influenced by geomorphic processes has a smaller width than does the undisturbed treeline ecotone (fig. 3).

In fact, in areas where the treeline is limited by merging deposits due to gravitational processes, the treeline and the timberline altitudes are approximately the same (mean width of the ecotone: 83 m; tab. 4). In some cases, the width of the treeline ecotone is reduced to zero (fig. 3), and the treeline overlaps the timberline (fig. 4).

In contrast, in areas where geomorphological processes have less of an impact on the position of the treeline, the treeline ecotone is wider. For example, in areas where the treeline altitude is limited by the presence of rock glaciers (fig. 5) or rills, the treeline ecotone has a mean width of 231 m and 229 m, respectively (tab. 4).

Finally, the chi-square tests (tab. 5) show that the geomorphological processes may alter the frequency distribution of trees (fig. 6). The chi-square test that took into consideration the frequency distributions of all landform types and the different classes of landforms (landforms due to running and/or channelized water, landforms due to gravity and landforms due to cryogenic processes) is significant at the $p<0.005$ level (tab. 5).

The chi-square value obtained for the comparison of the elevation of the trees limited by the merging and isolated gravity deposits is also significant at the $p<0.005$ level (tab. 5).

On the contrary, the value of the frequency distribution of landforms due to running and/or channelized waters (gullies, rills and alluvial cones) from the chi-square test is not significant at the $p<0.005$ level (tab. 5).

DISCUSSION

The current changes in climate conditions are driving huge modifications in sensitive environments. In high mountain landscapes, biological and abiological responses to climate change are particularly evident (Evans & Clague, 1994), both in terms of recent changes as well as in terms of ancient changes that have often reconstructed via the analysis of woody remains (Pelfini & *alii*, 2014). The shrinkage of glaciers is characterized by a general reduction in glacier surface area (Frezzotti & Orombelli, 2014), and the retreat of the glacier tongues is followed by a progressive increase in supraglacial debris induced by increasing slope processes (e.g., Haeberli & *alii*, 1997) and by an accelerated melting rate (Dyurgerov & Meier, 2000). The widening of the glacier forefields offers new habitat for animals and plants, including trees (Pelfini & *alii*, 2012; Garavaglia & *alii*, 2010). At the same time, valley slopes may experience an upward shift of the vegetation belts and, in particular, of the treeline. Different studies have shown that the altitudinal treelines, besides responding to climate (Holtmeier & Broll, 2007; Gehrig-Fasel & *alii*, 2008; Körner & Paulsen, 2004; MacDonald & *alii*, 2008),

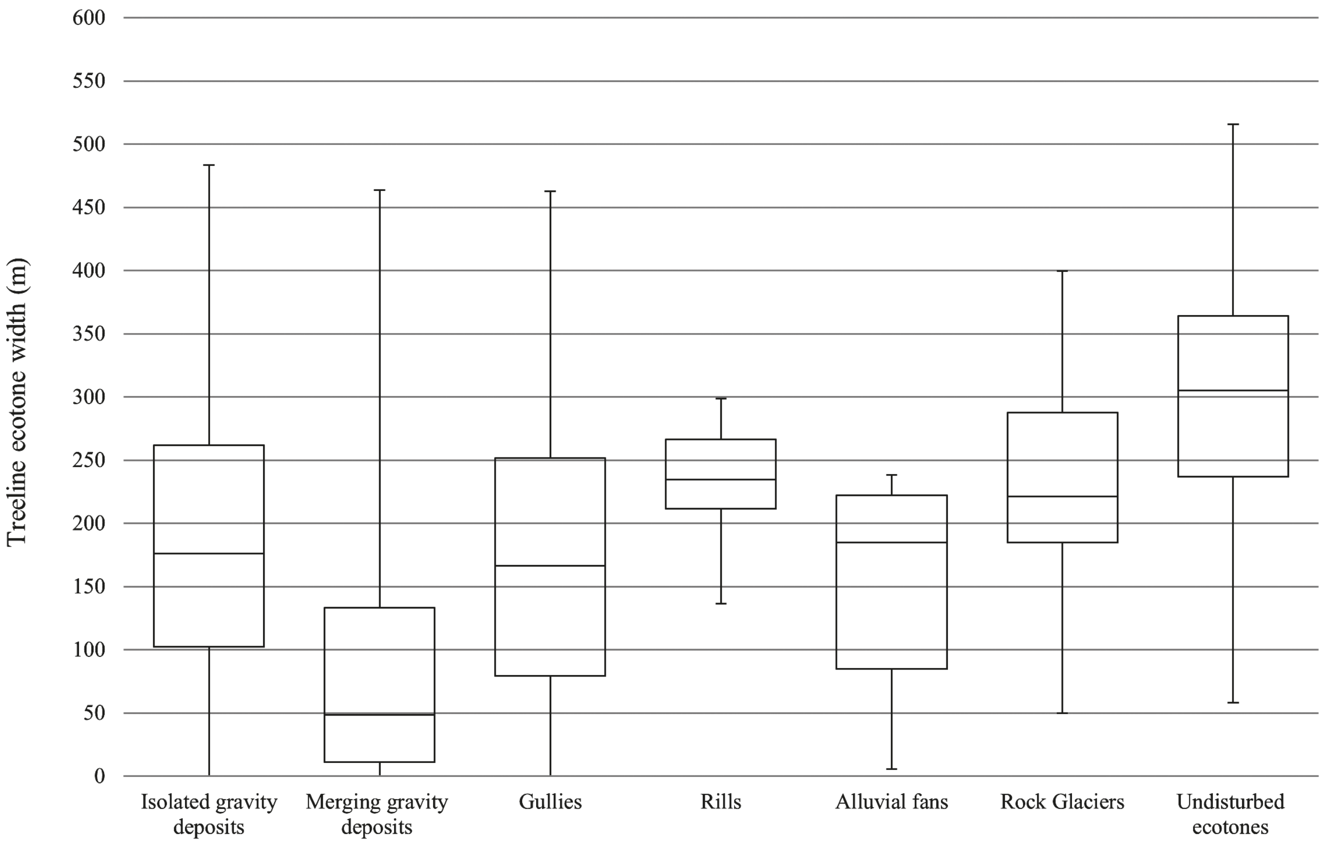

FIG. 3 - Distribution of treeline ecotone width, grouped according to the different landforms and geomorphological processes responsible for their positions, and the undisturbed ecotone. The whiskers of the box plots correspond to minimum and maximum values.

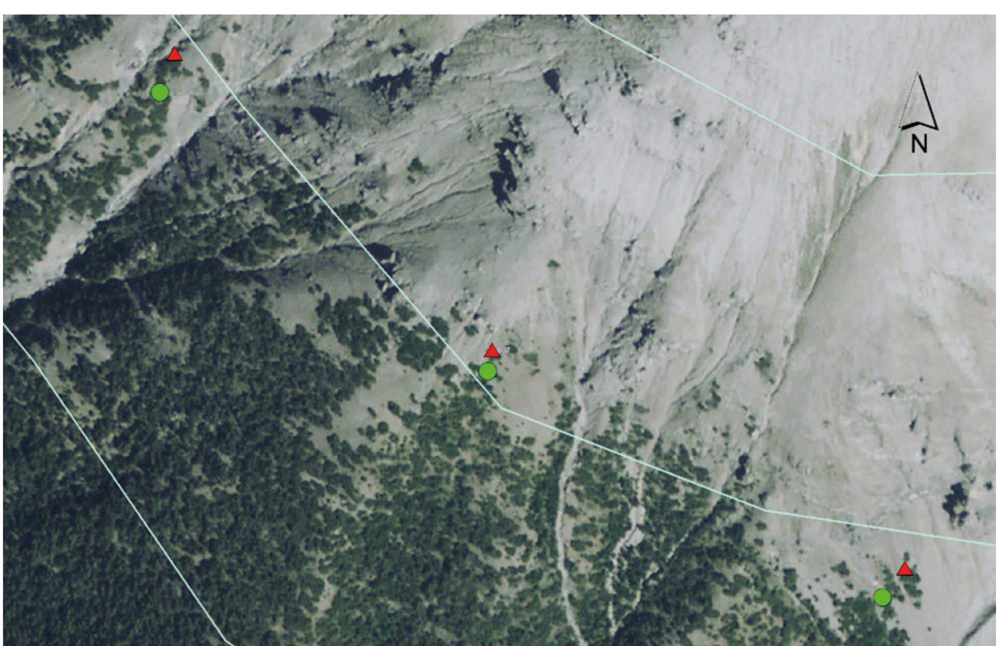

Fig. 4 - Examples of treeline trees (red triangles) constrained by the presence of merging landforms due to gravitational processes. The treeline trees and timberline trees (green dots) were located at approximately the same altitude of approximately 2300 m a.s.l.. The contour lines are placed at intervals of 100 m. The orthophoto has been analysed based on spatial data available from the National Geoportal (http://www.pcn.minambiente.it/GN/, WMS service). (Lat: 46° 33' 39.2"N Long: 10° 15' 56.4"E).

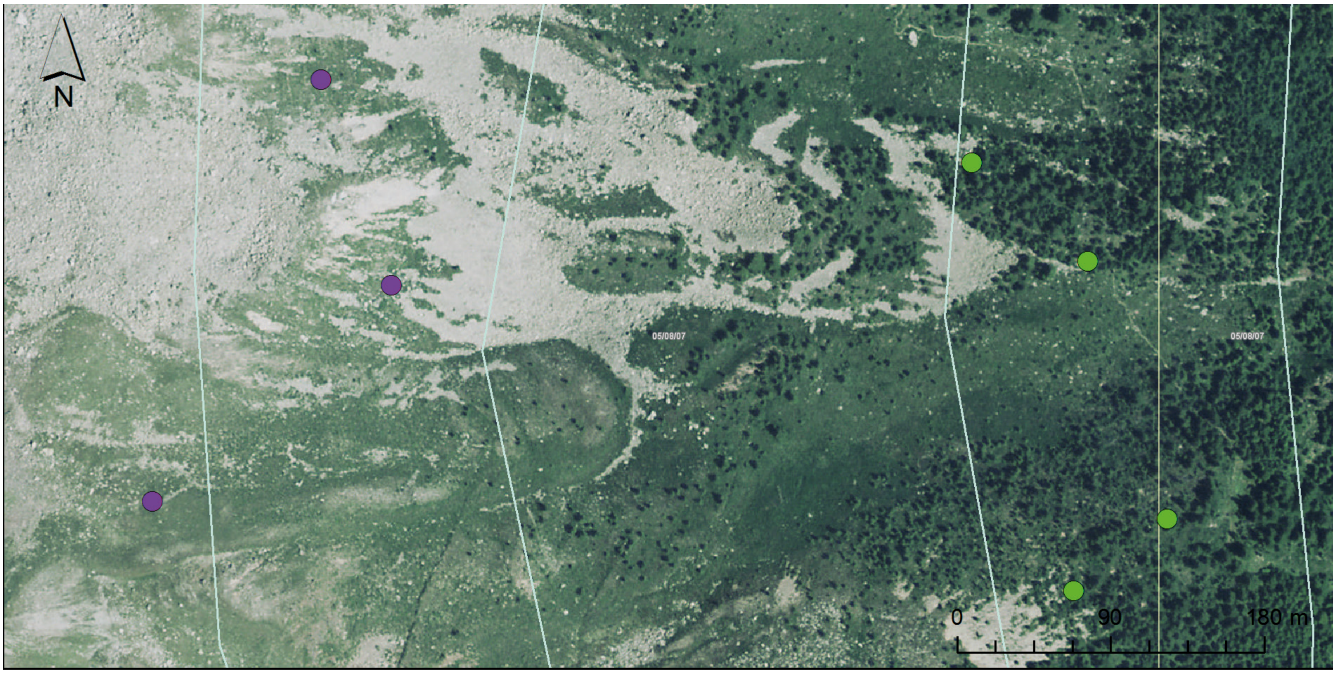

Fig. 5 - Examples of treeline trees (violet dots) constrained by the presence of landforms due to periglacial processes (i.e., rock glaciers). The treeline trees and timberline trees (green dots) were located at an approximate distance of 100 m. The contour lines are placed at intervals of 100 m. The orthophoto has been analysed based on spatial data available from the National Geoportal (http://www.pcn.minambiente.it/GN/, WMS service). (Lat: 46°22'12.5"N Long: 10°19'30.1"E).

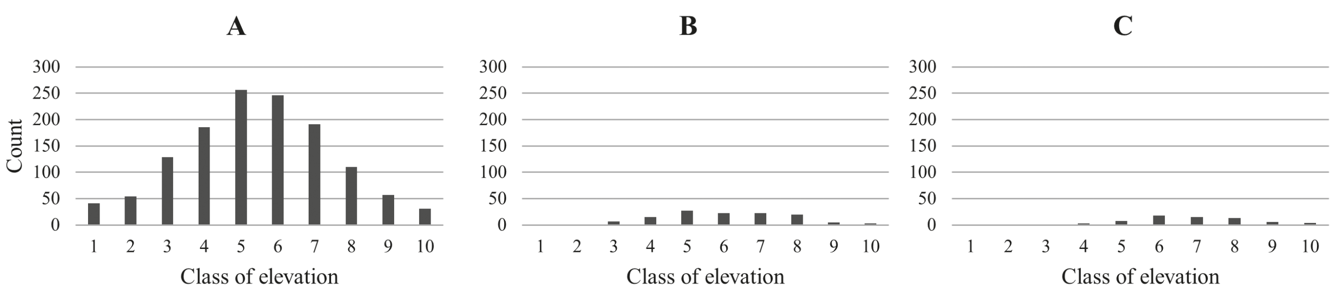

Fig. 6 - Distribution of the elevation variable for the analysed treeline trees subdivided by the three classes of landforms limiting the treeline elevation: (A) landforms due to gravity, (B) landforms due to running and/or channelized water, and (C) cryogenic landforms.

are also influenced by topography, landforms and related geomorphological processes occurring at high elevations (Butler & *alii*, 2007; Holtmeier & Broll 2012; Zald & *alii*, 2012; Leonelli & *alii*, 2016). The treelines limited by landforms and geomorphological processes are located at lower elevations than treelines constrained solely by climate (Leonelli & *alii*, 2009; 2011). Additionally, previous results obtained by studies in the same area show that the undisturbed treeline ("climatic treeline") is located at a higher altitude than the treelines limited by geomorphological processes (fig. 2A) (Leonelli & *alii*, 2016).

With this research, the relevance of the different geomorphological constraints on treeline has been statistically and spatially analysed and quantified in detail for the first time.

The analysis reveals that different geomorphological processes and related landforms may have different impacts on the treeline dynamics (fig. 2A). Mass movements and deposits due to gravitational processes are the most common in the Alpine environment (fig. 1). Therefore, instability phenomena and erosional and/or depositional processes related to gravity, as documented by the degree of landform activity, may be considered the most important controlling factors on the treeline position. Therefore, treelines affected by geomorphic processes can act as indicator of climate change.

The treeline trees affected by gravitational processes are located at lower altitudes than the trees limited by other processes (fig. 2A and tab. 4). Moreover, merging landforms derived from gravitational processes have a greater impact on treeline position than isolated landforms as they tend to eliminate free stable space for tree colonization. In areas where large portions of the valley slopes are covered by a continuous debris/block layer, a lower treeline altitude has been recorded. This means that the treeline altitude is differently affected not only by different geomorphological processes but also by the array of factors associated with landforms, such as size and rates of change (e.g., rock gelivity, fractures, precipitation, and time). While isolated deposits due to gravitational processes allow trees to colonize the surrounding areas and avoid the individual landforms, merging deposits influence the treeline altitude and reduce the treeline ecotone width, making recolonization more difficult.

Moreover, the merging deposits due to gravitational processes affect larger areas than the isolated ones and can in some cases also damage the forest, thereby depressing the timberline altitude (fig. 2B).

On the contrary, gully erosion has little impact on the treeline trees, firstly because the gullies in the examined ecotone are scattered and not continuous, allowing trees to colonize the neighbouring areas at the same altitude, and secondly because these processes generally do not affect the timberline (fig. 2B).

Rill erosion, even if only a few cases were available for analysis, represents a negligible factor in terms of the influence on the treeline position in the studied area because this geomorphological process can damage trees but does not seem to prevent their growth. Nevertheless, the lack of statistical difference in elevation distributions among the landforms due to running and/or channelized water is attributable mainly to the small number of trees limited by rills and small alluvial fans (tab. 5).

More data are likely necessary to assess the role of periglacial processes in the treeline ecotone. In the investigated area, such processes do not seem to be effective in lowering the treeline (fig. 2A). Moreover, rock glaciers may also represent an opportunity for tree germination and growth if they are inactive or relict. The stability of inactive rock glaciers and the presence of fine-grained soil material occurring in small pockets at the edge and at the front of active rock glaciers favour tree colonization (Burga & *alii*, 2004).

The results suggest that the timberline position is less influenced than the treeline position by geomorphological processes; this involves a reduction in the treeline ecotone width (fig. 3). Moreover, the analysis of the ecotone width reveals that the most impactful processes greatly reduce the width and that the treeline in most cases coincides with the timberline. The timberline altitude seems to be lowered only in some cases of extreme events associated with gravitational processes and in areas affected by alluvial cones.

In the first case, there is evidence of the destructive role of mass transport, while in the second case, the lowest position of the timberline seems most influenced by the presence of alluvial cones at low altitudes.

At the regional spatial scale, as in the case of our research, the destructive effects of geomorphological processes on the treeline are prevalent. Nevertheless, other studies carried out at the local scale show that geomorphological processes and landforms can also facilitate upward shifts in the treeline (Butler & *alii*, 2007; Resler, 2006). For example, the presence of boulders may moderate the temperature in close proximity to the block, providing plants with protection from severe weather and wind, may influence soil conditions, and may serve as seed traps (Resler & *alii*, 2005; Zald & *alii*, 2012).

Finally, the analysis of geomorphological factors can add more information about treeline response to climate change. Future upward shifts in treeline might be severely limited by geomorphic processes, which could become even more effective than at present in determining the distribution of trees at the highest elevations. In fact, if the temperature continues to increase, the upward shift in treeline will encounter harsher geomorphic environments that are not suitable for trees colonization (Macias Fauria & Johnson, 2013). Moreover, warmer temperature conditions will not cause an advance to higher elevations as long as mass wasting, landslides, and similar processes occur (Holtmeier & Broll, 2005).

CONCLUSIONS

The results presented in this paper indicate that the current positions of treelines are not only lowered by geomorphological constraints in general, as recently demonstrated (Leonelli & *alii*, 2016), but can also be differently affected by different groups or types of geomorphological processes. In the study area, gravitational processes affect 87% of the treeline trees, running and/or channelized water affects 8%, and ice affects only 5%. The landforms related to gravitational processes can create considerable obstacles to the upward shift in treeline, especially when they merge (e.g., merging talus cones). Gravitational processes represent the most destructive processes of the treeline ecotone and tend to reduce the ecotone width, leading to coinciding treeline and timberline.

These investigations into the roles of geomorphological factors in controlling the treeline altitude, by means of orthophoto and additional statistical analysis, represent an important step in assessing the current treeline position. The method allows rapid detection of regional or large-scale treelines and helps to quantify the influence of geomorphological processes on sensitive high-altitude vegetation.

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