Geografia Fisica e Dinamica Quaternaria
GFDQ 48 (2025), 73-89
DOI 10.4454/w5281929

Luca FORTI[1*], Manuela PELFINI[1], Pierluigi BRANDOLINI[2],
Joanna FIDELUS-ORZECHOWSKA[3], Stefano MOROSINI[4],
Andrea ZERBONI[1], Roberto Sergio AZZONI[1]

Human geomorphology in high mountain environment: 200 years of landscape transformation at Stelvio Pass (Central Alps, Italy)

Abstract: Forti L., Pelfini M., Brandolini P., Fidelus-Orzechowska J., Morosini S., Zerboni A., Azzoni R.S., *Human geomorphology in high mountain environment: 200 years of landscape transformation at Stelvio Pass (Central Alps, Italy).* (IT ISSN 0391-9838, 2025). The Stelvio Pass (2,758 m a.s.l., Central Italian Alps) represents a critical example of long-term human modification of high-mountain geomorphic systems. We combine multitemporal aerial and satellite imagery (1959-2023), historical sketch maps, historical photographs, land use/land cover (LULC) analysis and field-based geomorphological mapping to assess the extent and impacts of anthropogenic transformation. Since the mid-20th century, infrastructure development such as ski facilities, roadworks and artificial reservoirs has led to widespread slope reconfiguration, terrace construction and hydrological alteration. These modifications have affected periglacial dynamics, contributing to the formation of thermokarst depressions and active-layer thickening. Between 1959 and 2023, landscape fragmentation increased significantly, with a cumulative effect on geomorphic connectivity and slope stability. Vegetation monitoring highlights delayed colonisation on reworked substrates, influenced by compaction and poor soil development. The emergence of anthropogenic-periglacial systems underline the role of persistent human disturbance in driving geomorphic change. Our findings highlight the need for integrated monitoring and land management strategies to mitigate geomorphic hazards in climatically sensitive alpine environments.

Key words: Alpine geomorphology, Human geomorphology, Stelvio Pass, High-mountain environment.

Riassunto: Forti L., Pelfini M., Brandolini P., Fidelus-Orzechowska J., Morosini S., Zerboni A., Azzoni R.S., *Geomorfologia antropica in ambiente d'alta montagna: 200 anni di trasformazioni del paesaggio al Passo dello Stelvio (Alpi Centrali, Italia).* (IT ISSN 0391-9838, 2025). Il Passo dello Stelvio (2758 m s.l.m., Alpi Centrali) costituisce un caso emblematico di trasformazione antropica di lungo periodo nei sistemi geomorfici d'alta quota. L'analisi integrata di fotografie aeree e satellitari multi-temporali (1959-2023), cartografia storica, documentazione fotografica d'archivio, rilievi di uso/copertura del suolo e mappature geomorfologiche di terreno ha permesso di ricostruire l'evoluzione recente del paesaggio. A partire dalla metà del XX secolo lo sviluppo di infrastrutture turistiche e viarie e la realizzazione di bacini artificiali hanno determinato un profondo rimodellamento dei versanti, con sbancamenti, costruzione di terrazzamenti e modifiche dei regimi idrologici. Questi interventi hanno inciso sulle dinamiche periglaciali e hanno favorito la formazione di depressioni termocarsiche e l'ispessimento dello strato attivo. Tra il 1959 e il 2023 la frammentazione del paesaggio è aumentata in modo significativo, con effetti cumulativi sulla connettività e sulla stabilità dei versanti. Il monitoraggio della vegetazione ha mostrato una colonizzazione tardiva dei substrati rimaneggiati, condizionata dalla compattazione e dalla scarsa evoluzione pedogenetica. L'emergere di sistemi antropico-periglaciali mette in evidenza il ruolo dei disturbi antropici persistenti come fattori primari di cambiamento geomorfologici. I risultati evidenziano la necessità di un monitoraggio integrato e di strategie di gestione del territorio volte a mitigare i rischi geomorfologici in ambienti alpini particolarmente sensibili ai cambiamenti climatici.

Termini chiave: Geomorfologia alpina, Geomorfologia antropica, Passo dello Stelvio, Ambienti d'alta quota.

INTRODUCTION

Human geomorphology, the study of anthropogenic-induced alteration of surface processes and landforms, is central to understand present-day landscape evolution and trajectories (Hooke, 2000; Panizza, 1996; Goudie, 2018). While traditionally focused on lowlands and urbanised areas, mountainous environments have also undergone significant modifications due to infrastructure, tourism, sport and military activities (Beniston, 2003; Borgatti and

[1] *Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, Milan, Italy.*
[2] *Dipartimento di Scienze della Terra, dell'Ambiente e della Vita, Università degli Studi di Genova, Genova, Italy.*
[3] *Institute of Biology and Earth Sciences, University of the National Education Commission, Krakow, Poland.*
[4] *Dipartimento di Lingue, Letterature e Culture Straniere, Università degli Studi di Bergamo, Bergamo, Italy.*
* *Corresponding author: Luca Forti (luca.forti@unimi.it)*

Paper published on the 25th anniversary of AIGeo, the Italian Association of Physical Geography and Geomorphology. GFDQ vol. 48, Guest Editors: Pappalardo M., Rotigliano E., Ferrando A.

Soldati, 2005; Remondo *et al.*, 2005; Koppes and Montgomery, 2009; Latocha, 2009; Hewitt, 2014; Chakraborty, 2021). Across the Alps, the progressive retreat of glaciers, the intensification of tourism, and the expansion of infrastructure since the nineteenth century have jointly contributed to reshaping high-altitude landscapes, producing cumulative effects on slope dynamic, periglacial processes and geomorphic connectivity (Diolaiuti *et al.*, 2001; Borgatti and Soldati, 2005). In high-altitude environments such as the Italian Alps, human activities directly interact with glacial, paraglacial and periglacial processes as well as with slope dynamic. The Stelvio Pass (2,758 m a.s.l.) also known as Stilfser Joch in German, located in the Rhaetian Alps, connects the Braulio Valley (Valtellina, Lombardy) with the Trafoi Valley (Val Venosta, Trentino-Alto Adige) and it provides a clear example of natural and anthropogenic processes. Prior to the construction of the Stelvio Pass Road in 1825, the Braulio Valley was already crossed by a rudimentary mule track, which allowed the passage of goods and travellers across the alpine watershed, although with considerable difficulty and risk. Initially shaped mainly by high mountain processes, the area has been gradually altered by human activities related to cultural and economic factors (Società Economica Valtellinese, 2021). The construction of the Stelvio Pass Road in 1825 was a key development, cutting through steep slopes to create a strategic Alpine crossing (Panizza, 1996). Subsequent developments, including military and postal infrastructure as well as early tourism facilities, further modified the landscape (Cannone and Gerdol, 2003; Pelfini and Smiraglia, 2003). World War I left a persistent human signature on pristine landscape, with trenches, bomb craters, and fortified positions affecting the topography, slope stability and sediment dynamics (Hewitt, 2014; Hooke, 2000; Morosini, 2022). Organised ski tourism at Stelvio began to emerge in the interwar period, initially limited to seasonal activities supported by rudimentary facilities and a growing network of hiking trails that linked surviving World War I fortifications with panoramic viewpoints. However, the main phase of ski lift construction and slope preparation took place from the 1950s onwards, consistent with wider developments in the Alps (Diolaiuti *et al.*, 2001a, 2001b; Pelfini *et al.*, 2004, 2005, 2009). These combined initiatives reshaped the high-altitude landscape, intensifying human influence in a climatically sensitive environment. Modern interventions included the construction of ski lifts, ski slopes and artificial reservoirs, which fragmented landforms and ecosystems, disrupted periglacial processes and accelerated stream erosion (Knight and Harrison, 2014).Current concerns focus on the interactions between climate warming, permafrost degradation, and tourism-related infrastructure (Gruber and Haeberli, 2007; Diolaiuti *et al.*, 2021) resulting in accelerated changes of geomorphic diversity and local geoheritage along the Stelvio Pass area (Pelfini *et al.*, 2009). This study adopts a multitemporal approach to reconstruct two centuries of landscape evolution at the Stelvio Pass. The first objective is to examine how high-mountain terrain has responded to the combined effects of natural processes and long-term human modification. A further aim is to evaluate the role of infrastructure development, tourism, and military activities in modifying geomorphic systems and altering periglacial and paraglacial dynamics. Finally, the study seeks to contribute a detailed case study in Alpine human geomorphology, providing insights into ongoing landscape transformations in climatically sensitive environments.

GEOGRAPHICAL, GEOLOGICAL AND CLIMATIC BACKGROUND

The Stelvio Pass (2,758 m a.s.l.) develops within the Lombardy and Trentino Alto Adige Italian regions, is one of the highest paved mountains passes in Italy and it is part of the Stelvio National Park. It is surrounded by prominent peaks, including Ortles, Umbrail, and Scorluzzo, which are part of the Ortles-Cevedale Mountain Group (Guglielmin *et al.*, 2001) (fig. 1). For this study we mainly consider the Lombardy sector.

Geologically, the area around Stelvio Pass is composed of both sedimentary and metamorphic units. Sedimentary formations include limestones and dolomites, while the Bormio phyllites represent the dominant metamorphic lithology (Bonsignore *et al.*, 1969; Regione Lombardia - Servizio Geologico, 2001; Olvmo and Johansson, 2002). According to the most recent Alpine glacier inventory, based on Sentinel-2 imagery acquired in 2016 for this area (Paul *et al.*, 2019), four glaciers are present near the Stelvio Pass: in Lombardy, the Vitelli Glacier (1.18 km²) and the Platigliole glacier (0.08 km²); in Trentino Alto-Adige, the Madaccio/Madatsch Glacier (3.41 km²) and the Vedretta Piana/Eben Ferner (0.31 km²) (fig. 1). In recent decades, climate change has driven accelerated glacier retreat and the progressive widening of proglacial areas (D'Agata *et al.*, 2020). Climatic data from the nearest available meteorological station at Cancano (46°31′02.2″ N, 10°19′14.7″ E, 1,948 m a.s.l., located 9 km to the E-SE) for the period 1978-2015 indicate a mean annual air temperature of +3.3 ± 0.75°C. January is the coldest month (-5.2 ± 1.8°C), and July the warmest (+12.2 ± 1.6°C) (Malfasi and Cannone, 2020). Annual precipitation averages 810 mm, with 56% falling between May and September. Snowfall can occur year-round, but snow typically persists from mid-November to May. These climatic conditions strongly influence periglacial processes such as freeze-thaw dynamics and snow accumulation, which contribute to shaping of the local landscape (Cannone and Gerdol, 2003). As ice masses shrink, periglacial processes such as freeze-

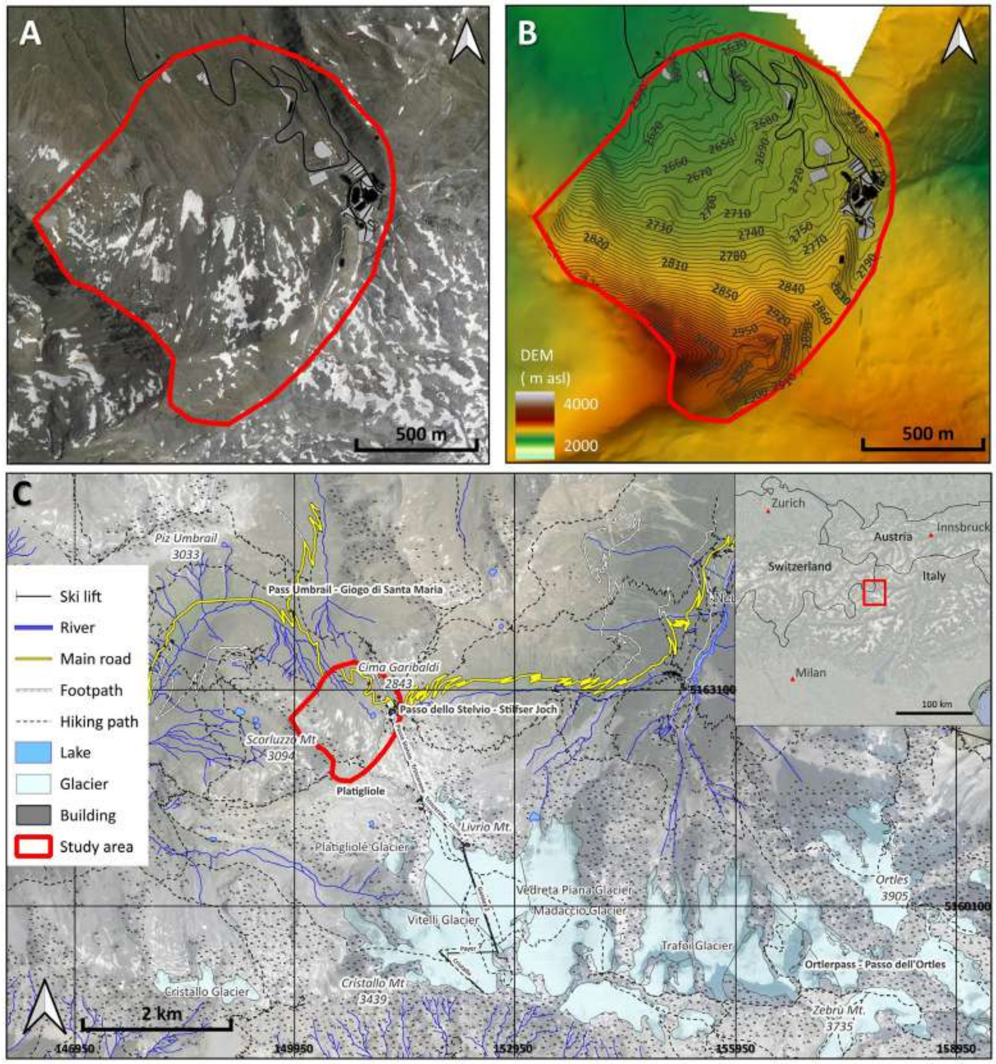

Figure 1 - (A) Google Earth-™ imagery showing the study area boundary. (B) Digital Elevation Model (DEM) (source Lombardy regional geoportal) with 10 m contour lines indicating topographic variation. (C) Detailed topographic map (extrapolated from Open Street Map and elaborated in QGIS) integrated with field data highlighting the main peaks, glaciers and places cited in the text.

thaw cycles and crionival activity become more dominant. Rock glaciers and patterned ground are widespread and serve as indicators of both current and past periglacial conditions (Cannone and Gerdol, 2003). Today, permafrost is mostly confined to localized zones such as ski slopes and rock glaciers, with its distribution governed by topographic and snow cover variability, which control ground insulation and radiation exposure (Haeberli and Beniston, 1998; Koppes and Montgomery, 2009; Guglielmin *et al.*, 2021).

HISTORICAL BACKGROUNDS

Road construction and its impact on the pristine setting of Stelvio Pass

The construction of the Stelvio Pass Road began in the early 19th century (fig. 2), at a time when improving transport routes through the Alps was a strategic priority (Società Economica Valtellinese, 2021). The first engineer involved was Filippo Ferranti, who was active in road construction projects in the lower Valtellina between 1820 and 1838. In 1812, Ferranti evaluated several possible routes, initially considering the Fraele Valley, but later selecting the Braulio Valley, which would ascend towards the Stelvio Pass. This route passed through the narrow and hazardous Braulio Gorge, historically used by travellers and crossed by three small bridges. The project was suspended in 1814 due to political and military instability as well as logistical challenges.

Following the formation of the Kingdom of Lombardy-Venetia in 1815, incorporated into the Austrian Empire, the road regained strategic importance, as a direct connection between Vienna and northern Italy became a key imperial objective. In 1817, Giuseppe Cusi replaced Ferranti and re-evaluated the project, proposing three options: the Fraele route, which he favoured; the Umbrail Valley; and the Stelvio Valley, which he considered too dangerous due to its altitude and avalanche risk.

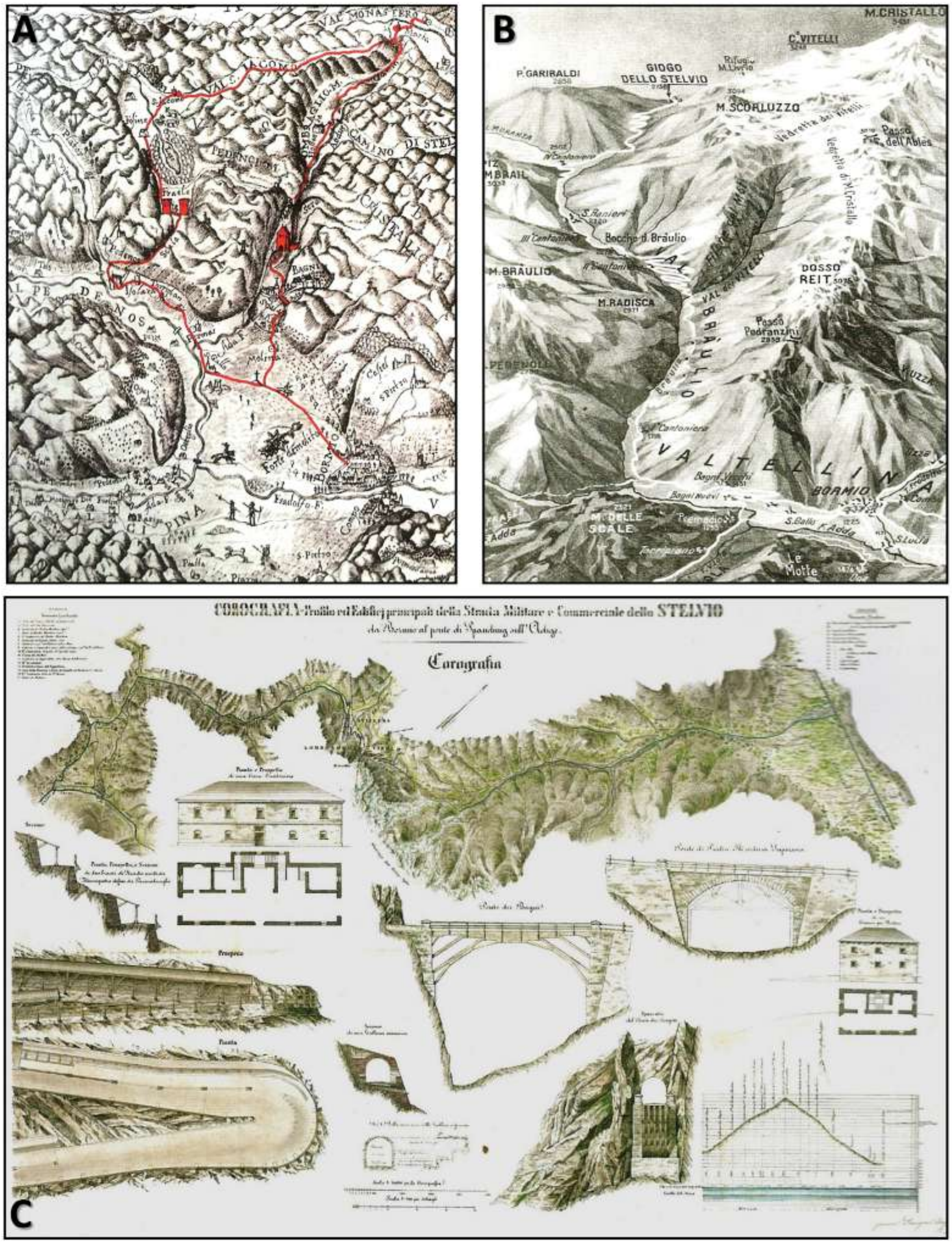

Figure 2 - Historical maps of the Stelvio Pass Road network and its evolution over time. (A) Map by H.C. Schnierl (1637) showing the ancient Umbrail and Fraele routes (in red) reworked by Patrick Cassitti (modified from: Società Economica Valtellinese, 2021). (B) Early 19th-century map (1815/1825) illustrating the development of the route through the Braulio Valley. (C) Chorographic map of the Stelvio road in mid-1800, including detailed architectural and engineering elements such as buildings, hairpin bends, and structural artifacts (Donegani, 1842).

In 1818, following technical errors in the assessments by Cusi and the surveyor Azzoni, the project was entrusted to engineer Carlo Donegani. Donegani resumed the work using Ferranti's previous surveys alongside new field data. In April 1820, he presented his project to the Viceroy of the Lombardy-Venetia Kingdom, Ranieri, and the plan was soon approved by the Austrian Emperor (Donegani, 1842). On 13 June 1820, the construction contract was awarded to Pietro Poli and Antonio Talacchini, and work started later that month. The first section, between Bormio and the Stelvio Pass, was completed in September 1824. The second section, from the pass to Prato/Prad, was assigned to Antonio Nolli in 1822 and completed in 1825. The third and final section, between Prato/Prad and Spondigna, began in October 1824 and was finished by April 1825. Despite prolonged interruptions during the winter months, the entire road was completed within five years and officially opened to traffic in October 1825 (Società Economica Valtellinese, 2021).

World War I: the "White War" and its influence on the landscape

During the World War I, the Stelvio Pass and the surrounding Ortles-Cevedale massif became part of the high-altitude front known as the "White War", where military operations unfolded at elevations exceeding 3,000 m

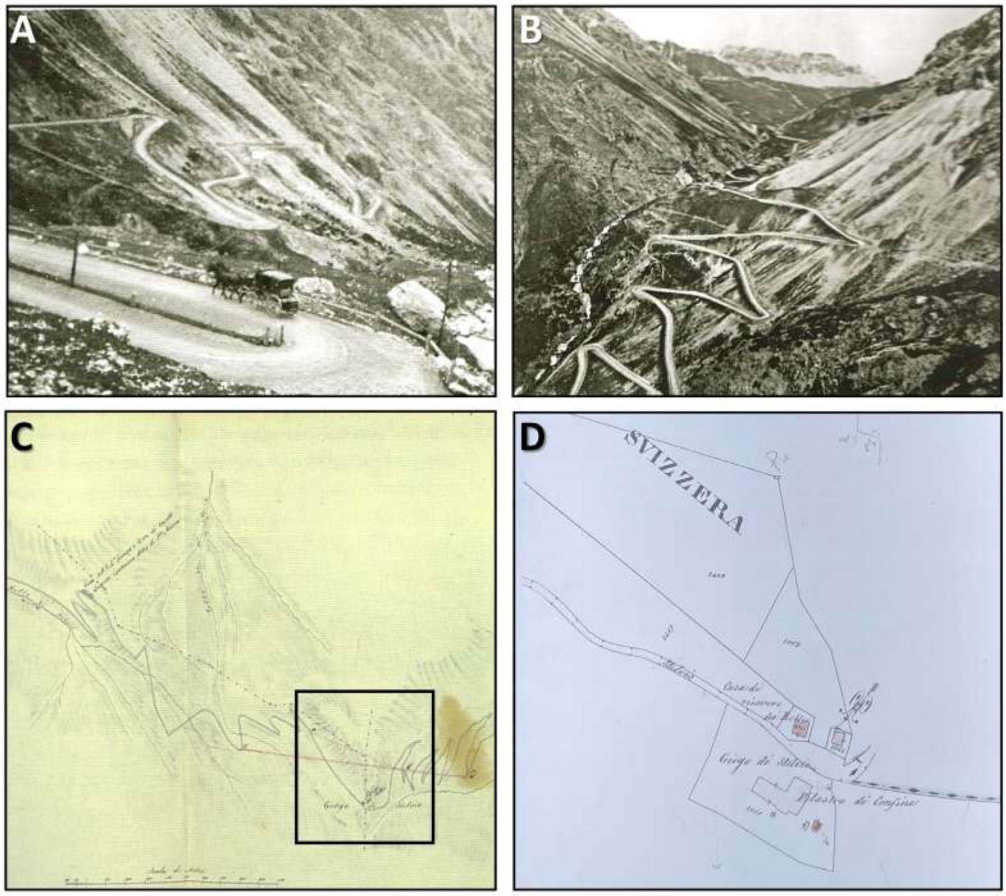

Figure 3 - Historical documentation of the Stelvio Pass Road network and its modifications over time. (A) Old photograph of a carriage descending along the Spondalunga section. (B) Oblique aerial view of the characteristic hairpin bends of Spondalunga. These photographs show the ancient road that is now closed to transit and has been replaced by a 20th-century variant in the Lombardy section. (C) Planimetric representation of the Stelvio road towards the pass, specifically the section between the 4th Cantoniera and the Bosco Cantoniera in the Trafoi Valley. The map highlights the selected location for the barracks and the planned perforations for tunnels aimed at mitigating the effects of rockfalls and prevent snow accumulation along the highest sections of the road; the inset is the position of D (modified from: Società Economica Valtellinese, 2021). D) Historical plan of the original buildings in the Stelvio Pass (1844).

a.s.l. In this harsh setting – characterised by frost weathering, strong wind, and seasonal snow cover – both Italian and Austro-Hungarian forces implemented extensive terrain modifications to secure strategic positions and ensure year-round logistical mobility. As highlighted by Morosini (2022), military infrastructures in the Stelvio sector represent a form of movement heritage, consisting of both material remains and landscape-scale transformations. In 1915, Austro-Hungarian troops constructed a cableway connecting the valley floor to Dreisprachenspitze (Cima Garibaldi, 2,843 m), enabling continuous supply over a vertical gradient of 1,245 m. This system redefined vertical connectivity in extreme alpine terrain, introducing infrastructural elements that altered slope dynamics and sediment redistribution. Scorluzzo Mt. (3,094 m) was a key node in this military landscape. Its ridge and summit were extensively fortified with dugouts, wooden barracks, and rock-cut defensive posts. The excavation of artificial shelters into bedrock and colluvial deposits modified the natural slope profiles and contributed to long-term instability of periglacial substrates. Field evidence documents trench systems (fig. 4A) and defensive posts (fig. 4B-C), illustrating how human intervention reshaped slope morphology and locally altered geomorphological processes. The WWI constructions acted as persistent geomorphic agents, producing slope disturbances, modifying hydrological pathways. Today, these relics function as both historical artefacts and diagnostic landforms, evidencing the entanglement of conflict, infrastructure, and high-mountain surface processes.

Post-World War I development and the rise of ski tourism (from 1920s to the late 20th century)

Human activity at the Stelvio Pass intensified after World War I. From the 1920s onwards, the area attracted visitors for hiking and mountaineering, building on the network of wartime mule tracks and trails that were gradually repurposed for recreational use (Pelfini and Smiraglia, 2003). The popularity of mountaineering increased during the interwar period, with the establishment of local Alpine clubs and the construction of mountain huts, which supported both summer hiking and high-altitude climbing activities (Garavaglia *et al.*, 2012).

However, it was ski tourism that brought about the most substantial environmental changes. The first ski lift was built in the 1950s, promoted by local hoteliers and the newly established SIFAS (Società Impianti Funiviari allo Stelvio), which became the main operator for ski facilities in the area (Diolaiuti *et al.*, 2001). This initial lift connected the Pass to Trincerone, linking the Nagler and Geister

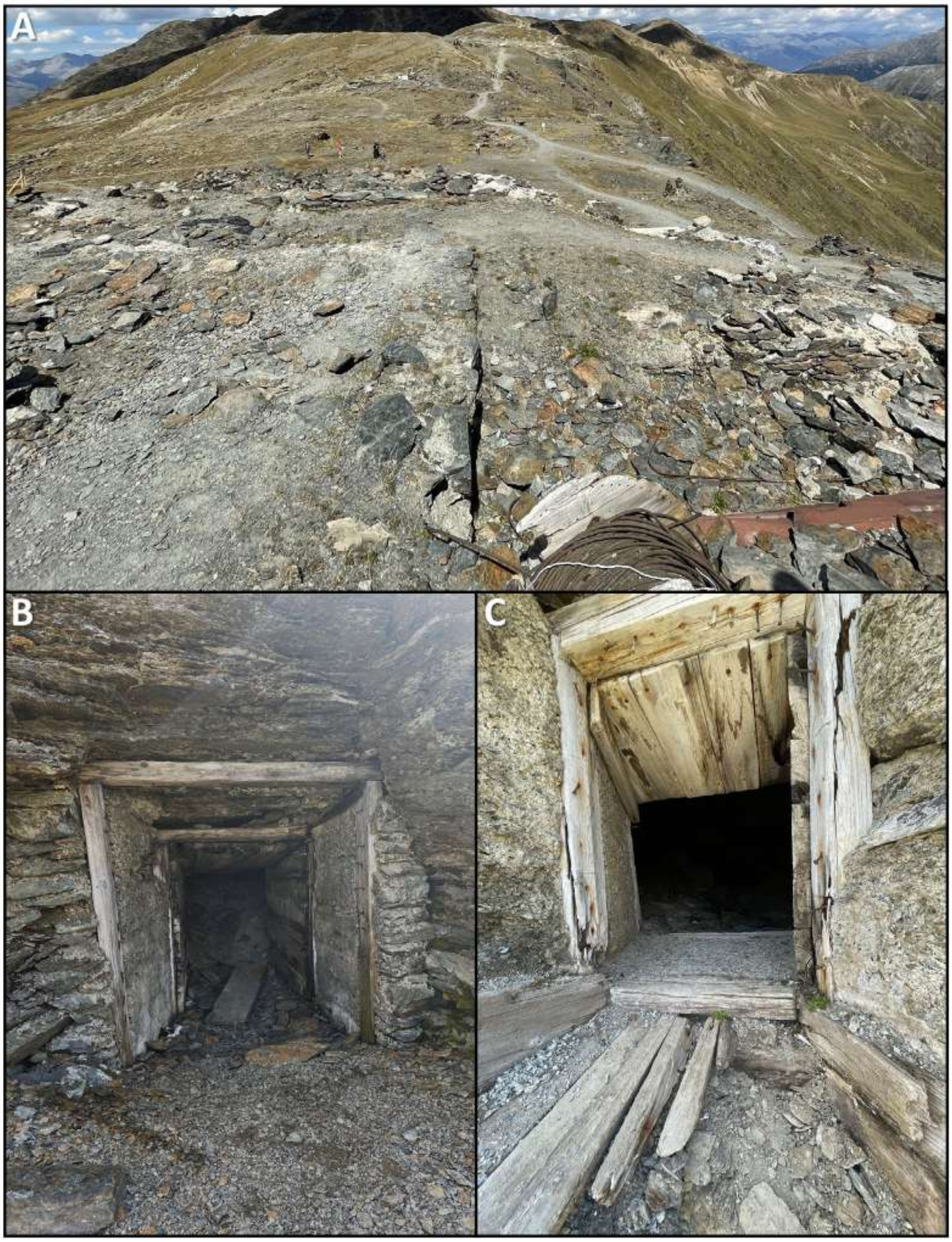

Figure 4 - World War I trenches (A) and defence posts (B-C).

slopes (figs 1 and 5). By 1965, the ski area was fully developed, with several lifts and groomed slopes, supported by hotels and permanent infrastructure.

The ski resort expansion involved extensive earthworks, slope reshaping, and the construction of service roads, significantly altering geomorphological processes. Vegetation monitoring in the Stelvio area (Cannone *et al.*, 2007; Malfasi and Cannone, 2020) documents ecesis (i.e. the time of initial establishment of plant species on bare or disturbed ground), which was often delayed or incomplete due to soil compaction, limited organic matter accumulation, and active frost processes. This resulted in patchy colonisation and increased susceptibility to erosion.

Permafrost in the Stelvio area is currently confined to high-altitude slopes, rock glaciers, and north-facing aspects, with its distribution strongly controlled by snow cover and local topography (Guglielmin *et al.*, 2021). Field and geophysical surveys confirm the presence of discontinuous permafrost in ski areas and adjacent debris slopes, raising concerns over the stability of infrastructure built on permafrost-affected terrain (Cannone *et al.*, 2003).

Artificial snow production has been practised since the late 20th century. Although systematic studies on its ecological impact at Stelvio are limited, evidence from comparable Alpine sites suggests potential effects on soil moisture, vegetation cover, and nutrient dynamics (Knight and Harrison, 2014; Guglielmin *et al.*, 2021). The interaction between artificial snow, grooming practices, and underlying permafrost is considered a key factor in recent geomorphological changes observed in the area.

MATERIALS AND METHODS

The reconstruction of the recent geomorphological evolution of the Stelvio Pass followed the approach proposed by Forti *et al.* (2022), based on multitemporal analyses of historical remotely sensed data. The study combined historical aerial photographs, satellite imagery, and declassified remote sensing data, enabling the reconstruction of landscape evolution and the assessment of both natural and anthropogenic changes. The analysis focused on the impacts of road construction, ski resort development, and multiple human activities that have progressively modified the area.

We used historical aerial imagery from the Swiss Geoportal, including flights dated 12 July 1946, 19 September 1959, 21 September 1966, and 10 August 1973 (ch.swisstopo.lubis-luftbilder_schwarzweiss). These were integrated with satellite data available in the regional archives for the years 1989 (Landsat TM, 30 m), 2003 (QuickBird, 2.5 m), 2021, and 2023 (Bolzano WMS service, https://home.provincia.bz.it/it/home; Lombardy Geoportal, https://www.geoportale.regione.lombardia.it/). The 2021 dataset was acquired on 15 July 2021 through the AGEA (Agenzia per le Erogazioni in Agricoltura) aerial photogrammetric programme, which provides high-resolution orthophotos for national cartographic coverage, with a ground spatial resolution of 0.20 m. The most recent imagery was acquired on 10 August 2023 through the Bolzano Province Geoportal and derived from the Pléiades Neo satellite constellation, also with a spatial resolution of 0.20 m.

Historical and recent images were used to map infrastructure expansion, ski area development, and changes in glacial and proglacial zones. Local changes in land use and land cover (LULC) were analysed using two main datasets: photointerpretation of the 1959 aerial imagery and the 2021 AGEA (Agenzia per le Erogazioni in Agricoltura) orthophotos, both sourced from the Lombardy Geoportal and analysed in QGIS. All spatial datasets were projected to UTM Zone 32. A detailed geomorphological map was pro-

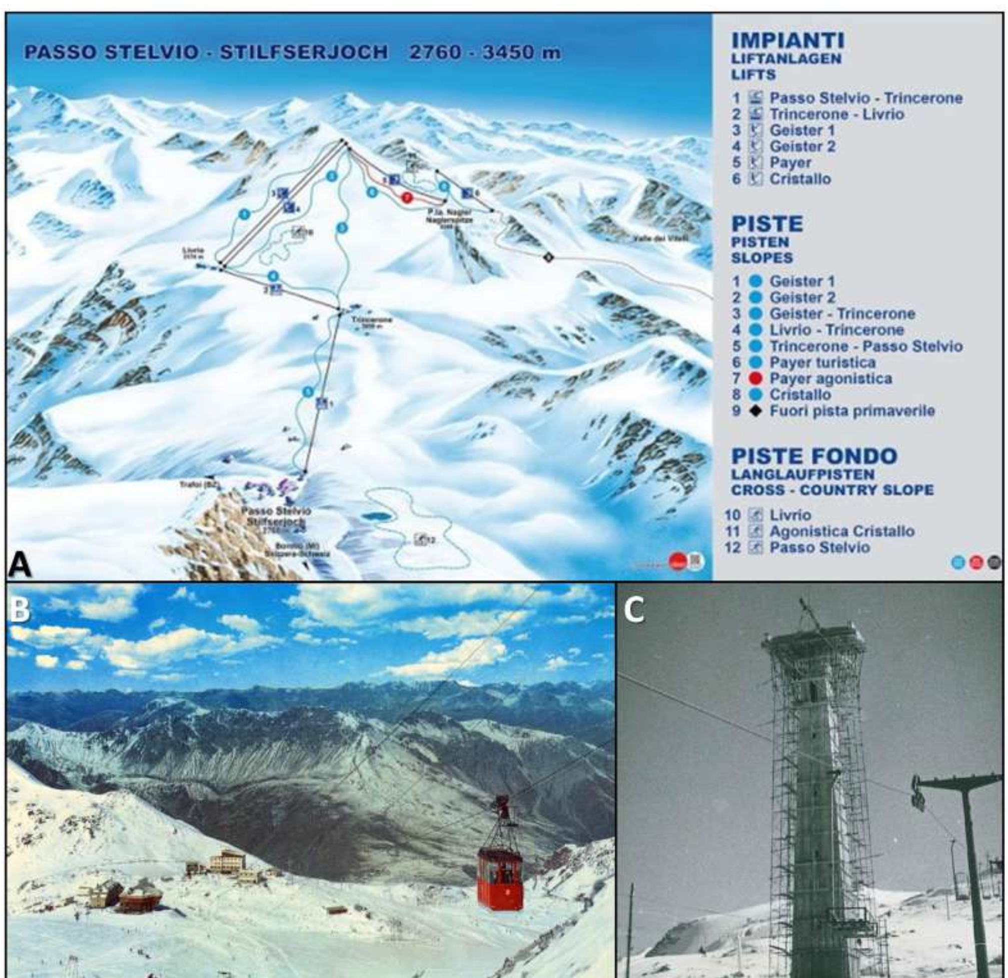

Figure 5 - The cable car infrastructure at Passo Stelvio. (A) Map of the ski lifts and slopes in the Stelvio area, indicating various facilities (https://www.passostelvio.eu/). (B) Historical view (ca 1978) of the cable car in operation, showing the connection between different sections of the ski resort (https://www.funivie.org/web/passo-stelvio-funivie-stelvio-trincerone-livrio/). (C) Construction phases of a cable car support tower, highlighting the engineering work required for high-altitude installations (1977) (https://www.funivie.org/web/passo-stelvio-funivie-stelvio-trincerone-livrio/).

duced using QGIS 3.34 (NextGIS, 2022). The base layers included a 5 × 5 m Digital Terrain Model (DTM) derived from the Lombardy Geoportal. Geomorphological features were mapped with the support of Pozzi *et al.* (1961), supplemented by the geological map of Alta Valtellina (Regione Lombardia – Servizio Geologico, 2001) and the regional ski domain map. Field surveys were carried out during the summers of 2022 and 2023 to validate photointerpretation results and to observe active geomorphological processes in situ. This integrated approach provided a comprehensive overview of landscape changes and allowed for the evaluation of the legacy of human intervention on the geomorphology of the Stelvio Pass.

RESULTS

Present-day geomorphological setting of the Stelvio Pass

The detailed geomorphological mapping of the Stelvio Pass region enabled the identification and classification of landforms according to the main geomorphic process (Campobasso *et al.*, 2018). Landforms classification is presented and discussed in the following part and reported in fig. 6 along with the main geological bedrock outcropping in the study area. Human agency on surface processes is further detailed in section 5.2.

Gravitative landforms

Gravity-driven processes are widespread across the area, primarily manifested as scree slopes and debris accumulations at the base of steep rock faces. Extensive debris deposits occur at the toe of Scorluzzo Mt. (fig. 7A) in the southwestern sector of the study area, resulting from gravitational mechanisms such as rockfalls, toppling, and shallow landslides. Areas affected by recent or ongoing gravitational processes include scattered fields of displaced rock debris associated with slope failure processes (figs 7A-C) (Ponti *et al.*, 2018; Longhi *et al.*, 2020; Guglielmin *et al.*, 2021; Longhi *et al.*, 2021).

Glacial, periglacial and crionival landforms

The Stelvio area preserves a clear record of past glaciations, marked by well-defined moraine ridges that indicate former glaciers' extent (fig. 6). Near the Scorluzzo rock glacier, moraines consisting of undifferentiated till testify to repeated glacial advances. Historical sources document that the Scorluzzo glacier persisted until 1937, when it still covered approximately 3 km², with the glacier tongue reaching an elevation of around 2,820 m a.s.l. (fig. 8A; Pelfini, 1992). The slopes surrounding the Stelvio Pass were mainly sculpted during the Pleistocene glaciations, with their present morphology largely inherited from the Last Glacial Maximum. Subsequent Holocene glacier advances, particularly those during the Little Ice Age, reworked these landforms without substantially altering their overall structure.

At present, the landscape exhibits a rich variety of periglacial and crionival features shaped by intense frost action and repeated freeze-thaw cycles. Solifluction and gelifluction lobes and sheets are widespread on the slopes (fig. 7A). Distinct lobate solifluction features are recognisable near the Platigliole Glacier, while higher elevations, above approximately 2,900 m a.s.l. and particularly on north-facing slopes, host crionival microforms linked to crionival creep and

Table 1: Database of historical aerial and satellite imagery used in this work.

Year	Data type	Source / Provider	Acquisition date	Sensor / Resolution	Colour / B&W
1946	Aerial photograph	Swiss Geoportal (https://www.geo.admin.ch/it)	12 Jul 1946	Analog / ~0.50 m	B&W
1959	Aerial photograph	Swiss Geoportal (https://www.geo.admin.ch/it)	19 Sep 1959	Analog / ~0.50 m	B&W
1966	Aerial photograph	Swiss Geoportal (https://www.geo.admin.ch/it)	21 Sep 1966	Analog / ~0.50 m	B&W
1973	Aerial photograph	Swiss Geoportal (https://www.geo.admin.ch/it)	10 Aug 1973	Analog / ~0.50 m	Colour
1989	Satellite image	Lombardy regional geoportal (https://www.geoportale.regione.lombardia.it/)	Not available	Landsat TM / 30 m	Colour
2003	Satellite image	Lombardy regional geoportal (https://www.geoportale.regione.lombardia.it/)	Not available	QuickBird / 2.5 m	Colour
2021	Satellite image	AGEA Lombardy Geoportal (https://www.geoportale.regione.lombardia.it/)	15 Jul 2021	AGEA aerial system / 0.20 m	Colour
2023	Satellite image	Bolzano Province Geoportal (https://natura-territorio.provincia.bz.it)	10 Aug 2023	Pléiades Neo / 0.20 m	Colour
2021	Digital Terrain Model	Regional archives (https://www.geoportale.regione.lombardia.it/)	2021	DTM 5 × 5 m resolution	–

gelifraction (fig. 7C) (Ponti *et al.*, 2018). The Scorluzzo rock glacier remains the most prominent periglacial landform, displaying lobate morphology and persistent downslope flow (fig. 7A-B). According to Cannone *et al.* (2003), this rock glacier predates the Little Ice Age, reflecting the long-term persistence of cryogenic processes. Contemporary climate warming, combined with ongoing anthropogenic disturbance, has markedly accelerated glacier retreat and permafrost degradation in the Stelvio region, as confirmed by micromorphological, geophysical, and stratigraphic studies (Guglielmin *et al.*, 2001; Ponti *et al.*, 2018; Longhi *et al.*, 2020; Guglielmin *et al.*, 2021; Longhi *et al.*, 2021).

Anthropogenic features

Significant anthropogenic alterations have reshaped the topography and landforms at Stelvio Pass. Infrastructures include paved roads (Stelvio and Umbrail Passes), unpaved access roads, extensive trekking paths, artificial reservoirs, ski slopes, and related facilities (figs 1, 6, 8C-D). Excavation and reshaping of slopes for ski infrastructure, such as the construction of the speed skiing track (fig. 8E), increased erosion rates, slope instability, and vegetation loss (Cannone *et al.*, 2003; Pelfini and Smiraglia, 2003; Belò *et al.*, 2005; Diolaiuti *et al.*, 2006). One of the rock glaciers in the area

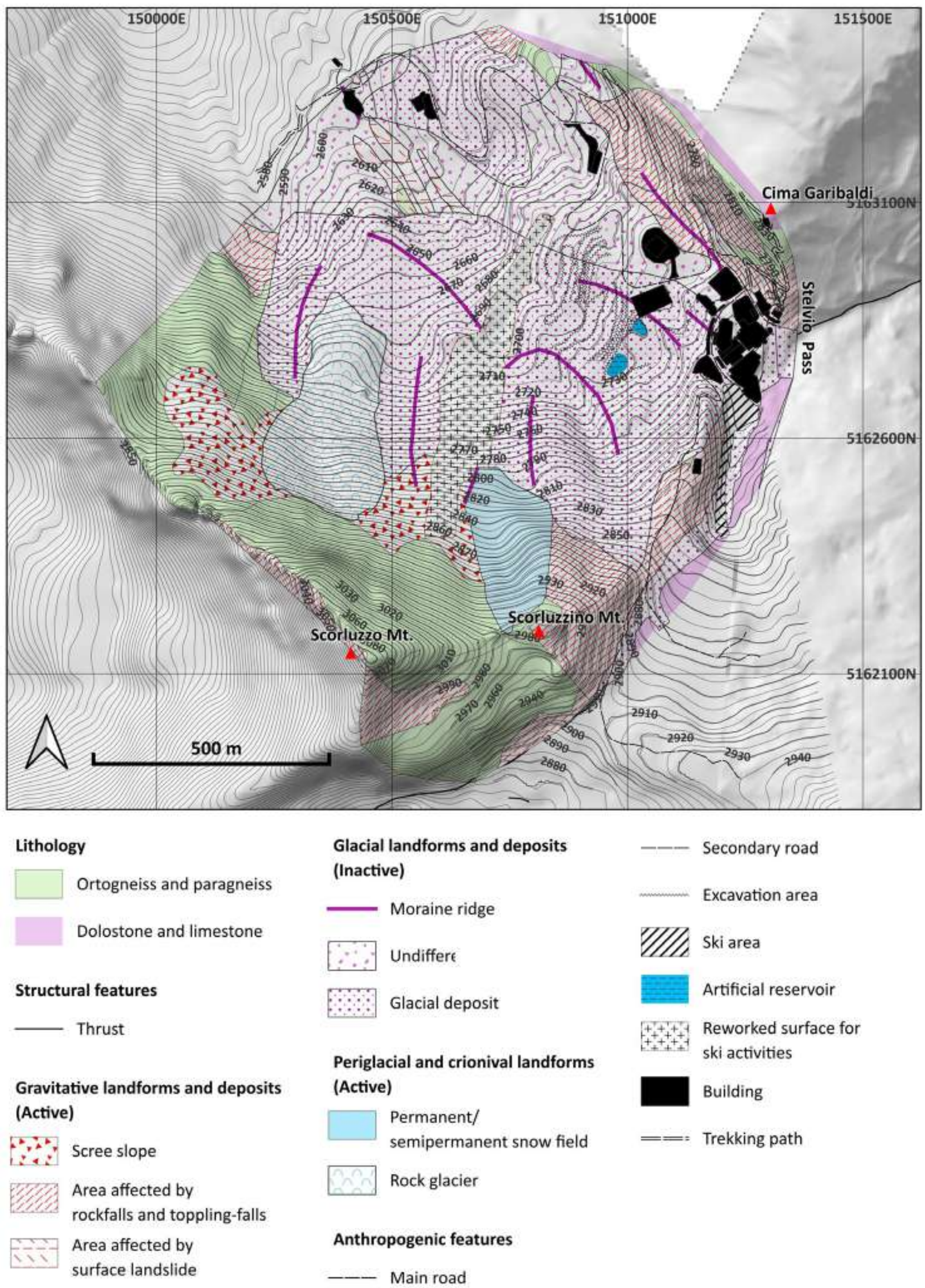

Figure 6 - Geomorphological sketch map reporting local lithological units and main landforms and deposits, including those related to human actions.

was bulldozed in 1987 to allow the construction of ski infrastructure (Cannone *et al.*, 2003). Other anthropogenic impacts include the construction of high-voltage power lines, parking areas, and numerous lodges and cantonments, cumulatively contributing to the substantial modification of the natural alpine geomorphological setting and reducing natural ground surfaces (Pelfini *et al.*, 2005; Garavaglia *et al.*, 2012; Goudie, 2018). These interventions have also altered hydrological connectivity, permafrost stability, and ecosystem dynamics, particularly in periglacial areas (Cannone *et al.*, 2003; Guglielmin *et al.*, 2021; Bollati *et al.*, 2023).

HUMAN GEOMORPHOLOGY ON THE STELVIO PASS

Evolution of anthropogenic landforms 1959-1989

The analysis of historical aerial imagery (1959, 1966, 1973, and 1989) reveals a progressive anthropogenic reshaping of the Stelvio Pass area. In 1959, the landscape remained largely natural, dominated by high-mountain processes and landforms such as scree slopes and glacial deposits, with minimal infrastructure concentrated near the pass (fig. 9A). By 1966, infrastructure expansion

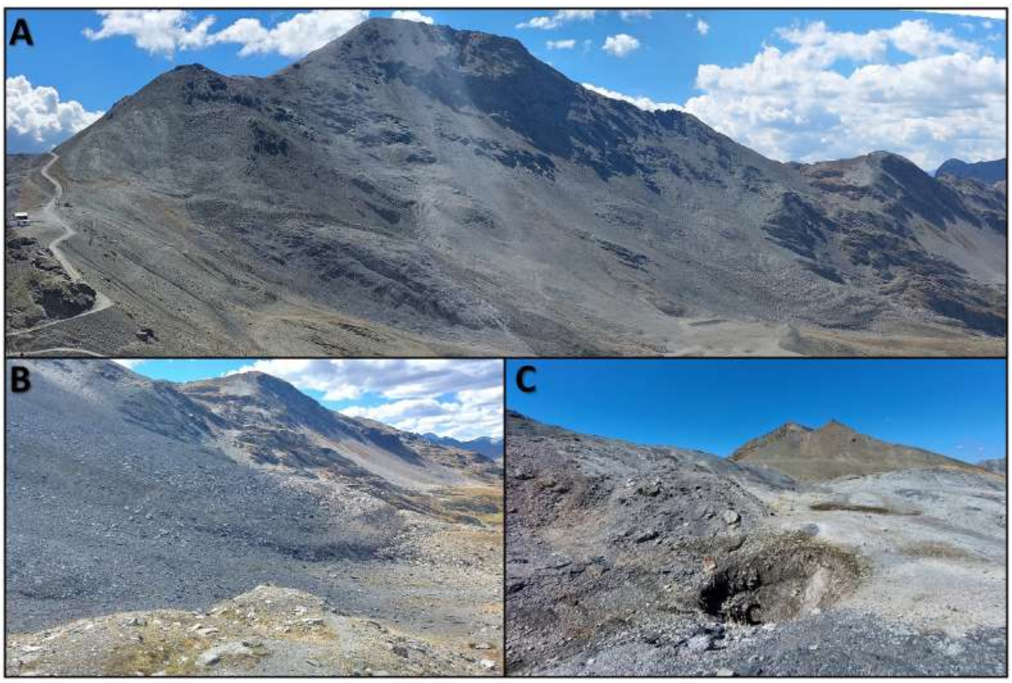

Figure 7 - Some pictures of the main geomorphological features of the area. (A) Scorluzzino Mt. one the left and Scorluzzo Mt. on the right. (B) Detail of the front of the Scorluzzo rock glacier. (C) Depression near ski slopes.

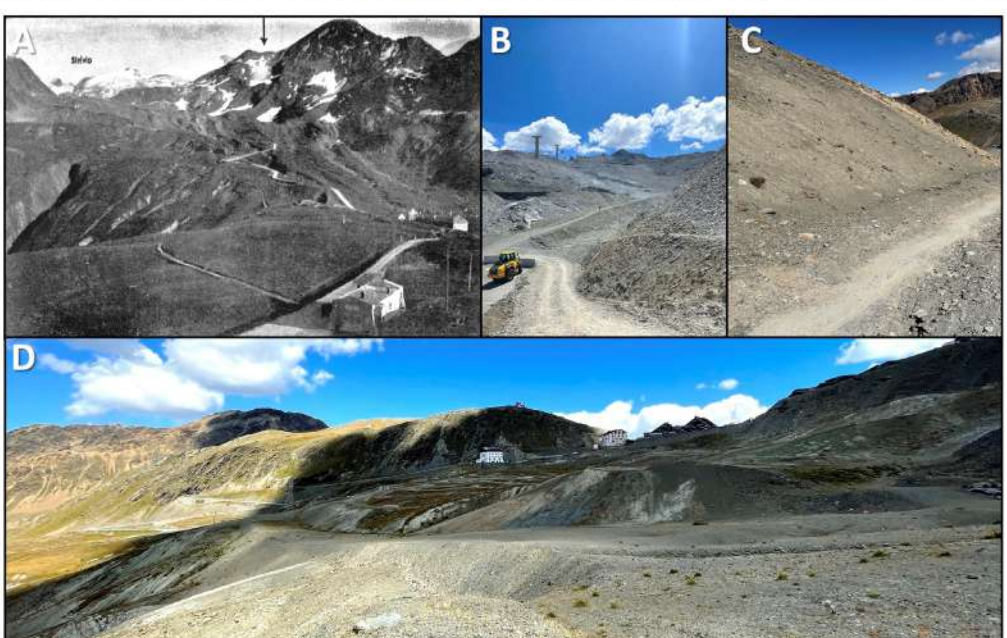

Figure 8 - (A) Scorluzzo glacier (now extinct) indicated by the arrow in 1930 (view from N). (B) Dirt road and unvegetated slopes reshaped by ski infrastructure development. (C) Slope along a trail showing accelerated erosion and debris accumulation. (D) Excavation associated with the construction of the speed ski track.

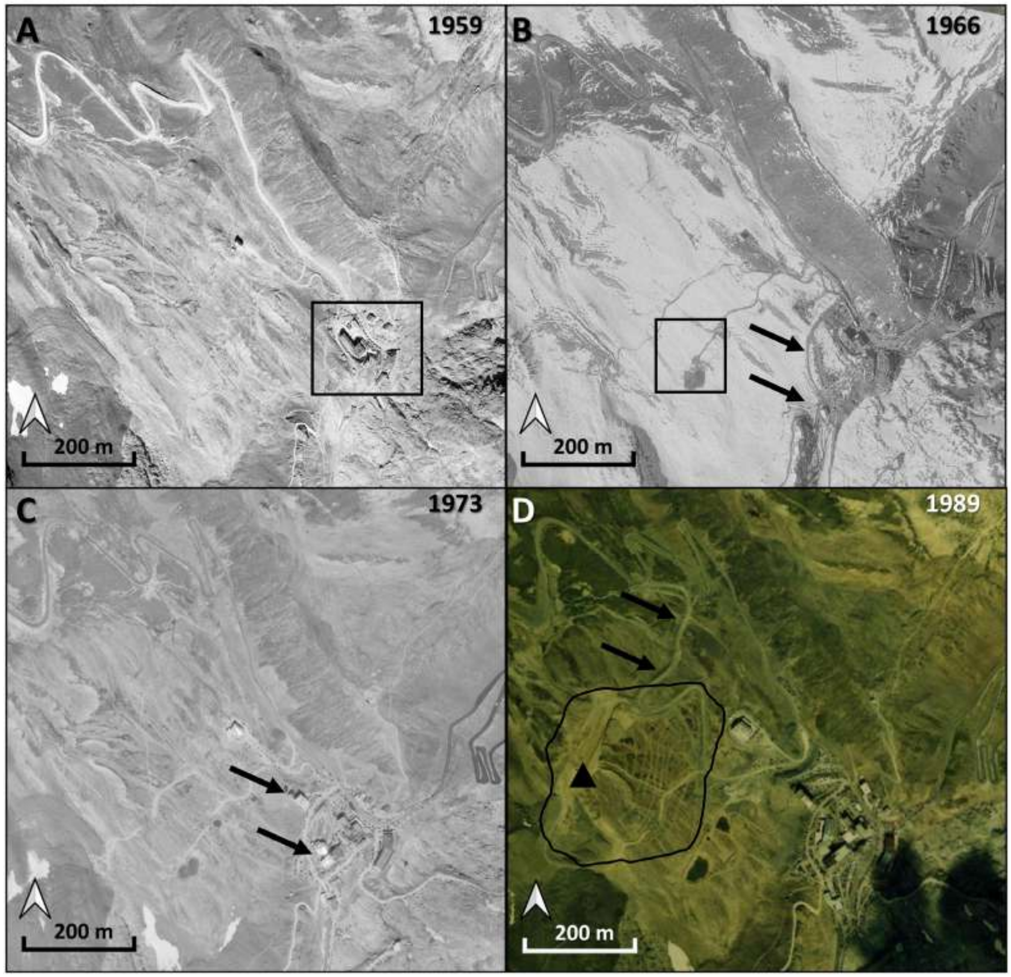

Figure 9 - Anthropogenic transformations at Stelvio Pass between 1959 and 1989. A) 1959 aerial imagery capturing the Stelvio Pass before the major impact of human modifications; only a few buildings are present (black polygon). B) 1966 aerial imagery highlighting human modifications; black arrows indicate parking areas and the box indicate artificial reservoirs for snow plan and a service road. C) 1973 aerial imagery showing increased infrastructural development, including new roads and buildings (black arrows), likely linked to the growth of ski facilities and tourism. D) 1989 Satellite imagery displaying extensive terrain reshaping and construction; black arrows indicate road development and ski infrastructure expansion, black triangle marks the creation of cross-country skiing trails, and the black outline shows the area of major topographic reconfiguration involving terracing and slope reprofiling.

had become more evident, including the development of parking areas and the construction of new buildings, roads, and artificial reservoirs for snowmaking (fig. 9B). Road embankments showed clear evidence of cut-and-fill operations. By 1973, infrastructural complexity had increased further, with the emergence of branching roads and additional buildings, likely reflecting the growing development of ski facilities and tourism activities (fig. 9C). By 1989, the landscape had undergone substantial modification, characterised by larger clusters of buildings, expanded access roads, and new or reprofiled terraces designed to manage slope gradients. Moreover, the expansion of ski infrastructure, from small-scale installations to more extensive lifts and tracks, and the construction of cross-country skiing trails further reshaped the topography, creating new pathways for erosion and affect patterns of runoff and sediment redistribution (fig. 9D). Several excavations were performed near the cross-country skiing tracks, to construct a new branch of the main road (fig. 9D) and to development mountains-sport related activities (ski, hiking, etc., fig. 9D).

Recent human agency 2003-2023

The 1989-2003 is not considered in detail because during this period we do not detect relevant anthropic geomorphological changes. Meanwhile comparison of satellite imagery from 2003 and 2023 highlights a slight intensification of anthropogenic impacts on the Stelvio Pass landscape. A major cross-country ski track – engineered through repeated cut-and-fill operations, the construction of drainage channels, and the installation of artificial water reservoirs – now stands as one of the most prominent landscape features (figs 7A, B, D). Artificial water reservoirs, excavated and sealed with artificial linings, modified the hydrogeological conditions at the local scale (Gerfand *et al.*, 2020; Louis *et al.*, 2025). In 2003, developed areas remained relatively similar, with limited terracing and infrastructure (fig. 10A). By 2023, no major new large-scale developments occurred, a cumulative proliferation of small-scale interventions had substantially reshaped slope morphology and increased landscape fragmentation (figs 10B, 10C). The realignment of older roads (figs 10A, 10B) to bring them closer to ski facilities represents a significant landscape modification, involving extensive earthworks such as slope cutting, filling, and stabilisation.

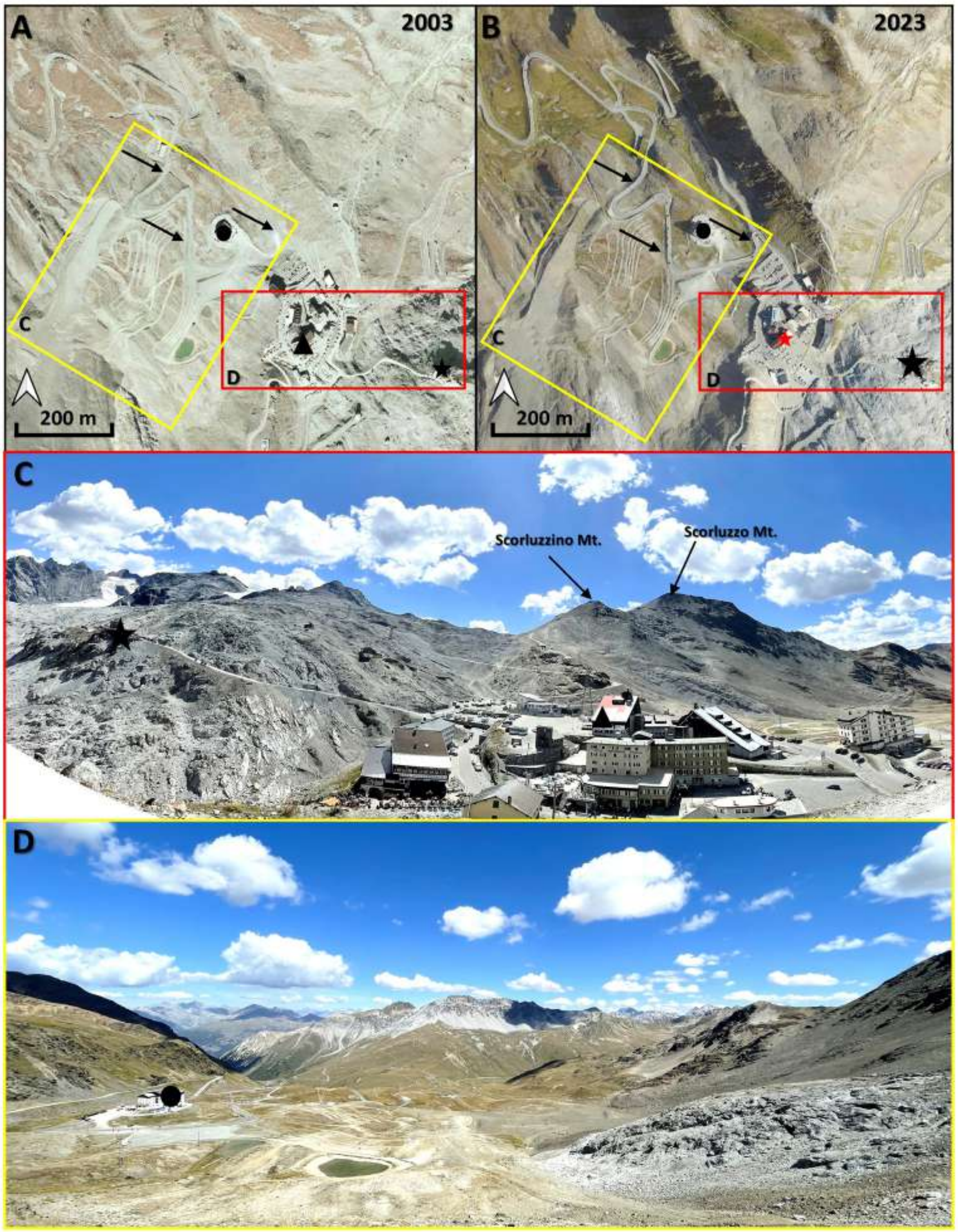

Figure 10 - A) 2003 Satellite imagery, illustrating the relatively limited extent of anthropogenic development, including a small cluster of buildings and modest terracing (black arrows indicate the construction phase of the new route) (the red box is the view in the picture C while the yellow one is the D). (B) 2023 Satellite imagery, highlighting the cross-country ski track and the realignment of roads (black arrows indicate the new route) (the red box is the view in the picture C while the yellow one is the D). (C) Panoramic view on the Stelvio Pass occupied by service buildings, parking facilities, and additional terraces, collectively reshaping the natural slope. (D) Field picture of the anthropogenic impact related to the construction of cross-country ski track and excavation of artificial water reservoir.

Land use and land cover changes 1959-2021

The land use and land cover (LULC) comparison between 1959 and 2021 reveals a marked shift from a landscape dominated by natural processes to the rapid increase of anthropogenic processes. In 1959, the area was characterised by extensive high-altitude grasslands, debris deposits, rocky outcrops, and sparse settlements (fig. 11A-C). Infrastructures were minimal, reflecting modest levels of tourism and seasonal activities. By 2021 (fig. 11B-D), the LULC pattern had changed substantially, with a visible expansion of the road network, the establishment of campsites and tourist accommodations, and the consolidation of built-up areas. Landscape modifications associated with the progressive development of road infrastructure, the construction of parking areas, and widespread cut-and-fill operations aimed at reshaping slope profiles have led to localised but significant changes of natural drainage networks (Cannone *et al.*, 2007). These anthropogenic interventions, designed to facilitate vehicular circulation, improve tourist accessibility, and accommodate increasing recreational demand, have disrupted the original geomorphological and ecological equilibrium, particularly in areas sensitive to freeze-thaw cycles and periglacial processes. Vegetation mapping from 2021 imagery (fig. 11D) indicates the persistence of sparse alpine plant communities. The detailed investigations in the area highlight a climate-driven up-

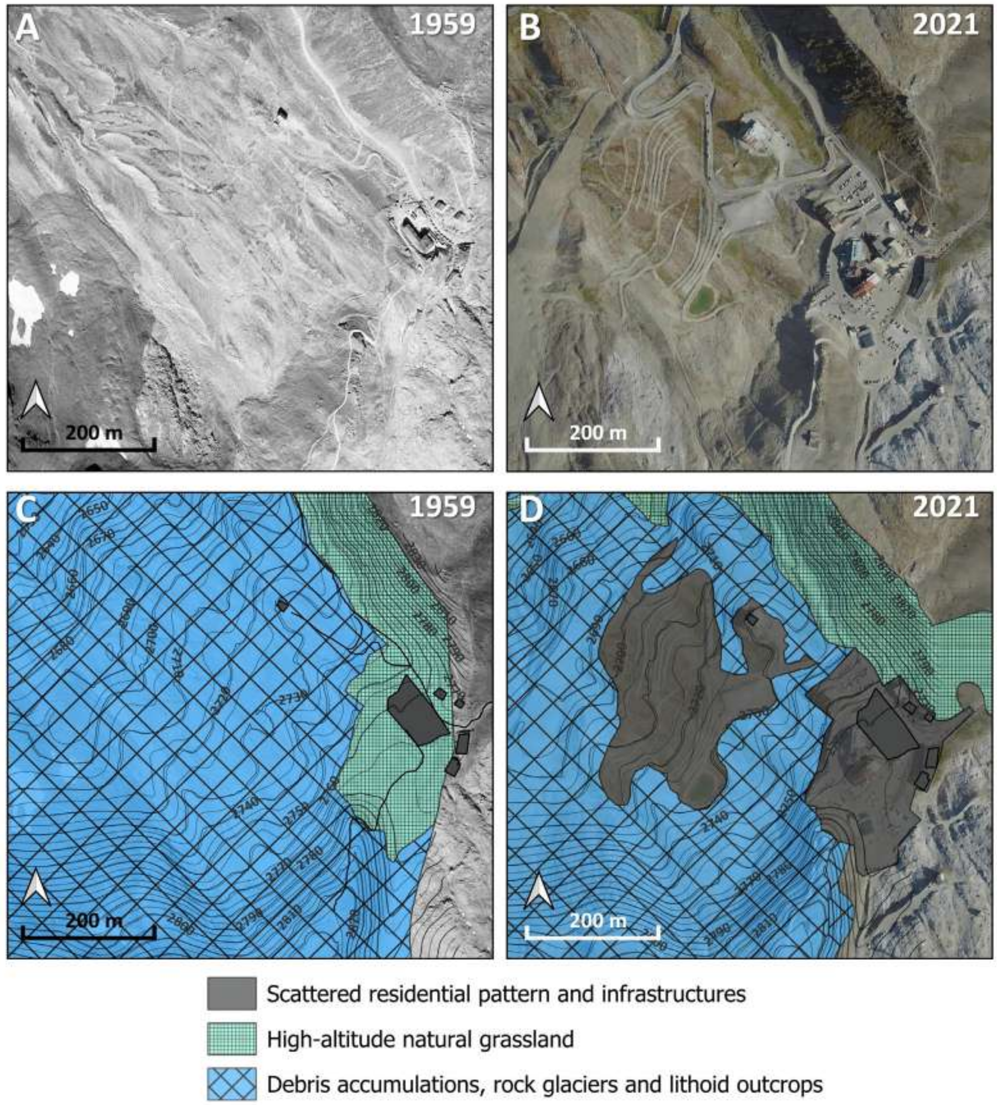

Figure 11 - Land use and land cover (LULC) classification of the Stelvio Pass area. A-C) Satellite imagery of 1959 and LULC map from 1959 showing a predominance of high-altitude grasslands, detrital deposits, and sparse built structures, reflecting a landscape mostly shaped by natural geomorphological processes. B-D) Satellite imagery of 2021 and LULC map from 2021 illustrating an expanded road network, campsites, tourist infrastructures, and more consolidated built-up areas, indicating intensified anthropogenic pressures.

ward migration of shrub and tree species particularly since the end of the Little Ice Age, as a response to persistent warming and reduced snow cover duration (Cannone *et al.* 2007; Malfasi and Cannone, 2020). These changes occurred largely independently of direct land use modifications. The increasing presence of woody vegetation at high elevations is also linked to enhanced microbial activity and soil enzymatic functions, with implications for nutrient cycling and carbon fluxes (D'Alò *et al.* 2021).

DISCUSSION

The geomorphological evolution of the Stelvio Pass area reflects the transition from a nature-dominated landscape to a palimpsest of natural and anthropogenic processes interacting at least since the building of the main road. Human-tuned processes and anthropogenic landforms have become progressively dominant over natural ones at least since the Great Acceleration (Shoshitaishvili, 2021; Steffen, 2021). The retreat of glaciers such as the Scorluzzo left behind relict moraines and newly exposed debris slopes prone to geomorphic instability. These transformations were already partially documented in early military cartography and descriptive accounts during World War I (Filippi, 1918).

Road construction and wartime interventions

The first major phase of anthropogenic modification began with engineering works led by Carlo Donegani. In 1842, cut and fill operations enabled horse-drawn carriages and later motor vehicles to cross one of the highest Alpine passes. These interventions improved connectivity but also introduced artificial slopes, retaining walls and embankments, altering slope stability and local drainage patterns with long-term geomorphological consequences (Panizza, 1996; Goudie, 2018; Guglielmin *et al.*, 2021). Subsequent road improvements, particularly near steep switchbacks, required further earthworks to ensure safety in avalanche-prone terrain and gravity induced mass transport (Haeberli and Beniston, 1998; Ponti *et al.*, 2018; Guglielmin *et al.*, 2021). During World War I, the Stelvio area underwent further transformations due to military infrastructure. Soldiers constructed trenches, rock shelters and cableways, many of which remain visible today and documented in recent conservation studies (Cardaci *et al.*, 2023). These wartime constructions fulfilled immediate tactical needs but also profoundly altered the geomorphological setting by triggering slope instabilities, removing vegetation and disrupting the periglacial equilibrium (Filippi, 1918; Cannone and Gerdol, 2003).

Tourism development and ski infrastructures

In the post-war period, tourism emerged as the dominant factor reshaping the high-altitude environment, particularly through the development of ski infrastructure (Diolaiuti *et al.*, 2001a, 2001b, 2006; Pelfini *et al.*, 2004, 2005, 2009). Initially minimal, tourism-related infrastructure expanded progressively, with the construction of ski lifts, terracing, access roads and parking areas altering glacial and periglacial landforms (Belò *et al.*, 2005; Smiraglia *et al.*, 2015). From the 1960s onwards, ski-related development intensified (Diolaiuti *et al.*, 2001b; Pelfini *et al.*, 2004). Excavation and slope reshaping for ski infrastructure, such as the construction of the speed skiing track, increased erosion rates, slope instability and vegetation loss (Cannone *et al.*, 2003; Pelfini and Smiraglia, 2003; Belò *et al.*, 2005; Diolaiuti *et al.*, 2006). These interventions also altered hydrological connectivity, permafrost stability and ecosystem dynamics, particularly in periglacial areas (Cannone *et al.*, 2003; Guglielmin *et al.*, 2021; Bollati *et al.*, 2023) in the post-war period, tourism emerged as the dominant factor reshaping the high-altitude environment, particularly through the development of ski infrastructure (Diolaiuti *et al.*, 2001a, 2001b, 2006; Pelfini *et al.*, 2004, 2005, 2009) and the valorisation of the local hiking trails that link remnants of fortified positions with panoramic points. Initially minimal, tourism-related infrastructure expanded progressively, with the construction of ski lifts, terracing, access roads and parking areas altering glacial and periglacial landforms (Belò *et al.*, 2005; Smiraglia *et al.*, 2015). From the 1960s onwards, ski-related development intensified (Diolaiuti *et al.*, 2001b; Pelfini *et al.*, 2004), interacting with geomorphological dynamics such as run-off, erosion, permafrost processes and slope stability (Schrott and Sass, 2008; Knight and Harrison, 2013; Ponti *et al.*, 2018; D'Alò *et al.*, 2021; Guglielmin *et al.*, 2021).

Climate change and periglacial response

Rising air temperatures have played a major role in driving widespread glacier retreat and the progressive degradation of alpine permafrost (Harris *et al.*, 2003); in the study region, long term measurements performed by Guglielmin *et al.* (2018) confirmed the Alpine general trend and suggest the local relevance of permafrost. Frost weathering processes such as cryoclastism, needle ice formation and frost heave contribute to the mechanical disintegration of exposed rock surfaces, producing large volumes of debris accumulated at the base of steep slopes (Ponti *et al.*, 2018; Longhi *et al.*, 2020; Guglielmin *et al.*, 2021; Longhi *et al.*, 2021). Thermokarst depressions, observed in ski areas at Stelvio, expanded rapidly since the early 2000s (Guglielmin *et al.*, 2021), accompanied by shifts in soil moisture regimes. Enhanced microbial activity in warming soils alters biogeochemical cycling and may influence soil stability and nutrient availability (D'Alò *et al.*, 2021; Sannino *et al.*, 2021). Vegetation monitoring confirms an upward migration of shrub and tree species, with shrub encroachment and tree ingression affecting soil development and erosion resistance (Cannone *et al.*, 2007; Malfasi and Cannone, 2020). Colonisation of disturbed substrates remains delayed, influenced by compaction and poor soil development, with feedback on microbial diversity and enzymatic activity (D'Alò *et al.*, 2021; Sannino *et al.*, 2021).

Our multitemporal and geomorphological analysis, integrating historical aerial photographs, satellite imagery and high-resolution mapping, confirms and quantifies these transformations, showing that between 1959 and 2021 the extent of human infrastructures increased by nearly sixteen times (+1468%), largely at the expense of natural grasslands. This clear shift from a glacial- and periglacial-dominated landscape to one increasingly shaped by anthropogenic-periglacial systems provides a robust case study for assessing the cumulative impact of persistent human disturbance in climatically sensitive alpine environments (Diolaiuti *et al.*, 2001a; Cannone *et al.*, 2003; Garavaglia and Pelfini, 2011; Garavaglia *et al.*, 2012; Knight and Harrison, 2013; Goudie, 2018; Guglielmin *et al.*, 2021; Locatelli and Martinelli, 2023).

CONCLUSION

Our approach allowed us to reconstruct two centuries of landscape evolution at Stelvio Pass, highlighting three major results.

i. The gradual exposure of unstable glacial landforms (e.g., moraines and debris slopes) following glacier retreat allowed the intensification of human exploitation of the area and the modification of recently exposed landforms and deposits.

ii. The investigation of historical data permitted the definition of the long-term effects of progressively increasing transportation and recreational infrastructure: from 19th-century road works to WWI interventions up to modern ski facilities, human agency affected slope stability, drainage networks, and periglacial processes.
iii. Our data also suggest the progressive upward shift of vegetation and a delayed colonisation in anthropogenically disturbed substrates. Moreover, we notice the onset of hybrid anthropogenic-periglacial dynamics that increase the fragmentation of surfaces and geomorphic processes, potentially boosting surface instability.

At present, ski infrastructure is experiencing a phase of maximum decline, with many low-altitude facilities abandoned or unused. This trend suggests that no further anthropogenic pressure will expand onto the glacierized areas, while instead the role of Stelvio Pass as a hub for transit and alternative forms of tourism is being reinforced.

More in general, this case study improves our knowledge of the combined effects of climate-driven and human-driven geomorphic processes in terms of accelerated geomorphic transformation of high-mountain environments, ultimately suggesting the importance of targeted environmental monitoring, including revegetation plans and permafrost control, to support sustainable land management.

ACKNOWLEDGMENTS

We thank Valentina Falgari for supporting the collection of historical documents. The authors gratefully acknowledge the Stelvio National Park administration for granting research permits and providing invaluable support throughout the study. Funding was provided by Italian Ministry of University and Research (Grant PRIN202223RAZZO, GEOTRes – Geoheritage threating and resilience: mapping the impact of geomorphic and human processes in sensitive morphoclimatic environments; entrusted to RSA). Part of the research was supported by the Italian Ministry of Universities and Research through the project "Dipartimenti di Eccellenza 2023-2027", awarded to the Dipartimento di Scienze della Terra "A. Desio" of the Università degli Studi di Milano (WP2 and WP3). Additional finantcial support from "Piano di sostegno alla ricerca: Linea 2, azione A anno 2023" P.I. RSA.

REFERENCES

Azzoni R.S., Pelfini M., Zerboni A., 2023. *Estimating the evolution of a post-Little Ice Age deglaciated Alpine valley through the DEM of difference (DoD).* Remote Sensing, 15, 3190. https://doi.org/10.3390/rs15123190

Belò M., Diolaiuti G., Pelfini M., Smiraglia C., 2005. *Un nuovo tema di ricerca in glaciologia applicata: l'utilizzo turistico dei ghiacciai, conoscenze attuali e risultati del primo studio pilota sulle Alpi Italiane.* In: Terranova R., Brandolini P., Firpo M. (Eds), La valorizzazione turistica dello spazio fisico come via alla salvaguardia ambientale, 317-344. Patron, Bologna.

Beniston M., 2003. *Climatic change in mountain regions: a review of possible impacts.* Climatic Change, 59, 5-31. https://doi.org/10.1023/A:1024458411589

Benn D.I., Evans D.J.A., 2010. *Glaciers and glaciation* (2nd ed.). Routledge, London, 816 pp.

Bollati I.M., Viani C., Masseroli A., Mortara G., Testa B., Tronti G., Pelfini M., Reynard E., 2023. *Geodiversity of proglacial areas and implications for the geosystem services: a review.* Geomorphology, 108517. https://doi.org/10.1016/j.geomorph.2022.108517

Bonsignore G., Borgo A., Gelati R., Montrasio A., Potenza R., Pozzi R., Schiavinato G., 1969. *Note illustrative della Carta Geologica d'Italia, Foglio 8-Bormio.* Servizio Geologico d'Italia, Roma.

Borgatti L., Soldati M., 2005. *Geomorphological hazard and human impact in mountain environments: an introduction.* Geomorphology, 66 (1-4), 7-11. https://doi.org/10.1016/j.geomorph.2004.10.001

Campobasso, C., Carton, A., Chelli, A., D'Orefice, M., Dramis, F., Graciotti, R., Guida, D., Pambianchi, G., Peduto, F. Pellegrini, L., 2018. *Aggiornamento ed integrazioni delle Linee Guida della Carta Geomorfologica d'Italia alla scala 1: 50.000-Progetto CARG: modifiche ed integrazioni al Quaderno n. 4/1994.* I Quaderni, serie III del Servizio Geologico d'Italia (SGI), 13 (1), 1-95.

Cannone N., Gerdol R., 2003. *Vegetation as an ecological indicator of surface instability in rock glaciers.* Arctic, Antarctic, and Alpine Research, 35 (3), 384-390. https://doi.org/10.1657/1523-0430(2003)035[0384:VAAEIO]2.0.CO;2

Cannone N., Guglielmin M., Hauck C., Vonder Mühll D., 2003. *The impact of recent glacier fluctuation and human activities on permafrost distribution, Stelvio Pass (Italian Central-Eastern Alps).* In: Phillips M., Springman S.M., Arenson L.U. (Eds), Permafrost, 125-130. Swets & Zeitlinger, Lisse.

Cannone N., Sgorbati S., Guglielmin M., 2007. *Unexpected impacts of climate change on alpine vegetation.* Frontiers in Ecology and the Environment, 5 (7), 360-364. https://doi.org/10.1890/1540-9295(2007)5[360:UIOCCO]2.0.CO;2

Cardaci A., Azzola P., Versaci A., 2023. *High-altitude architecture and landscape: a survey for the conservation of military works at the Stelvio Pass.* Disegno, 12, 195-208. https://doi.org/10.26375/disegno.12.2023.20

Chakraborty A., 2021. *Mountains as vulnerable places: a global synthesis of changing mountain systems in the Anthropocene.* GeoJournal, 86 (2), 585-604. https://doi.org/10.1007/s10708-019-10079-1

D'Agata C., Diolaiuti G., Maragno D., Smiraglia C., Pelfini M., 2020. *Climate change effects on landscape and environment in glacierized Alpine areas: retreating glaciers and enlarging forelands in the Bernina group (Italy) in the period 1954-2007.* Geology, Ecology, and Landscapes, 4 (1), 71-86. https://doi.org/10.1080/24749508.2019.1585658

D'Alò F., Odriozola I., Baldrian P., Zucconi L., Ripa C., Cannone N., Malfasi F., Brancaleoni L., Onofri S., 2021. *Microbial activity in alpine soils under climate change.* Science of the Total Environment, 783, 147012. https://doi.org/10.1016/j.scitotenv.2021.147012

Diolaiuti G., D'Agata C., Pavan M., Vassena G., Lanzi C., Pinoli M., Pelfini M., Pecci M., Smiraglia C., 2001. *The physical evolution of and the anthropic impact on a glacier subjected to a high influx of tourists: Vedretta Piana Glacier (Italian Alps).* Geografia Fisica e Dinamica Quaternaria, 24, 199-201. https://www.gfdq.glaciologia.it/index.php/GFDQ/article/view/434

Diolaiuti G., Maugeri M., Senese A., Panizza M., Ambrosini R., Ficetola G.F., Parolini M., Fugazza D., Traversa G., Scaccia D., Franceschini M., Citron L., Pelfini M., 2021. *Immersive and virtual tools to see and understand climate change impacts on glaciers: a new challenge for scientific dissemination and inclusive education.* Geografia Fisica e Dinamica Quaternaria, 44 (1), 67-77. https://doi.org/10.4461/GFDQ.2021.44.6

Diolaiuti G., Pelfini M., Smiraglia C., Codazza V., 2001b. *Il turismo estivo al Passo dello Stelvio (Alpi Centrali); problemi e prospettive della fruizione antropica di un ghiacciaio alpino in un'area protetta*. Geotema, 15, 42-55.

Diolaiuti G., Smiraglia C., Pelfini M., Belò M., Pavan M., Vassena G., 2006. *The recent evolution of an Alpine glacier used for summer skiing (Vedretta Piana, Stelvio Pass, Italy).* Cold Regions Science and Technology, 44 (3), 206-216. https://doi.org/10.1016/j.coldregions.2005.11.006

Donegani C., 1842. *Relazione tecnica sulla costruzione della strada dello Stelvio*. Stamperia Reale, Milano.

Filippi F. de, 1918. *The geography of the Italian front*. The Geographical Journal, 51 (2), 65-75.

Ficetola, G. F., Marta, S., Guerrieri, A., Cantera, I., Bonin, A., Cauvy-Fraunié, S., Carteron, A. (2024). *The development of terrestrial ecosystems emerging after glacier retreat*. Nature, 632(8024), 336-342. https://doi.org/10.1038/s41586-024-07778-2

Forti L., Mariani G.S., Brandolini F., Pezzotta A., Zerboni A., 2022. *Declassified intelligence satellite imagery as a tool to reconstruct past landforms and surface processes: the submerged riverscape of the Tigris River below the Mosul Dam Lake, Iraq*. Earth Surface Processes and Landforms, 47 (10), 2483-2499. https://doi.org/10.1002/esp.5389

Franzetti A., Pittino F., Gandolfi I., Azzoni R.S., Diolaiuti G., Smiraglia, C, Ambrosini, R., 2020. *Early ecological succession patterns of bacterial, fungal and plant communities along a chronosequence in a recently deglaciated area of the Italian Alps.* FEMS Microbiology Ecology, 96 (10), fiaa165. https://doi.org/10.1093/femsec/fiaa165

Garavaglia V., Diolaiuti G., Smiraglia C., Pasquale V., Pelfini M., 2012. *Evaluating tourist perception of environmental changes as a contribution to managing natural resources in glacierized areas: a case study of the Forni Glacier (Stelvio National Park, Italian Alps).* Environmental Management, 50 (6), 1125-1138. https://doi.org/10.1007/s00267-012-9948-9

Garavaglia V., Pelfini M., 2011. *Glacial geomorphosites and related landforms: a proposal for a dendrogeomorphological approach and educational trails*. Geoheritage, 3, 15-25. https://doi.org/10.1007/s12371-010-0027-4

Garavaglia V., Pelfini M., Bollati I., 2010. *The influence of climate change on glacier geomorphosites: the case of two Italian glaciers investigated through dendrochronology.* Géomorphologie: relief, processus, environnement, 2, 153-164. https://doi.org/10.4000/geomorphologie.7895

Gerfand B., Arthaud F., Evette A., Testi B., Peyras L., Gaucherand S., 2025. *Ecological quality of snowmaking reservoirs in the Alps and management perspectives*. Aquatic Sciences, 87 (1), 1-14. https://doi.org/10.1007/s00027-024-01136-0

Goudie A., 2018. *Human impact on the natural environment: past, present and future.* Wiley-Blackwell, Chichester, 480 pp.

Gruber S., Haeberli W., 2007. *Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change*. Journal of Geophysical Research: Earth Surface, 112 (F2). https://doi.org/10.1029/2006JF000547

Guglielmin M., Cannone N., Dramis F., 2001. *Permafrost-glacial evolution during the Holocene in the Italian Central Alps*. Permafrost and Periglacial Processes, 12 (2), 111-124. https://doi.org/10.1002/ppp.379

Guglielmin M., Donatelli M., Semplice M., Serra Capizzano S., 2018. *Ground surface temperature reconstruction for the last 500 years obtained from permafrost temperatures observed in the SHARE STELVIO Borehole*. Climate of the Past, 14 (5), 709-724. https://doi.org/10.5194/cp-14-709-2018, 2018.

Guglielmin M., Ponti S., Forte E., Cannone N., 2021. *Recent thermokarst evolution in the Italian Central Alps*. Permafrost and Periglacial Processes, 32 (2), 299-317. https://doi.org/10.1002/ppp.2099

Haeberli W., Beniston M., 1998. *Climate change and its impacts on glaciers and permafrost in the Alps*. Ambio, 27 (4), 258-265. https://www.jstor.org/stable/4314732

Harris C., Vonder Mühll D., Isaksen K., Haeberli W., *et al.*, 2003. *Warming permafrost in European mountains*. Global and Planetary Change, 39 (3-4), 215-225. https://doi.org/10.1016/j.gloplacha.2003.04.001

Hewitt K., 2014. *Glaciers of the Karakoram Himalaya: glacial environments, processes, hazards and resources*. Springer, Dordrech, 383 pp.

Hooke R. LeB., 2000. *On the history of humans as geomorphic agents*. GSA Today, 10 (9), 4-10.

James L.A., Hodgson M.E., Ghoshal S., Latiolais M.M., 2012. *Geomorphic change detection using historic maps and DEM differencing: the temporal dimension of geospatial analysis*. Geomorphology, 137(1), 181-198. https://doi.org/10.1016/j.geomorph.2010.10.039

Knight J., Harrison S., 2013. *The impacts of climate change on terrestrial Earth surface systems*. Nature Climate Change, 3, 24-29. https://doi.org/10.1038/nclimate1660

Knight J., Harrison S., 2014. *Mountain glacial and paraglacial environments under global climate change: lessons from the past, future directions and policy implications*. Geografiska Annaler: Series A, Physical Geography, 96 (3), 245-264. https://doi.org/10.1111/geoa.12051

Koppes M., Montgomery D., 2009. *The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales*. Nature Geoscience, 2 (9), 644-647. https://doi.org/10.1038/ngeo616

Latocha A., 2009. *Land-use changes and longer-term human-environment interactions in a mountain region (Sudetes Mountains, Poland).* Geomorphology, 108 (1-2), 48-57. https://doi.org/10.1016/j.geomorph.2008.02.019

Leonelli, G., Masseroli, A., Trombino, L., Golzio, A., Bonetti, A., Maggi, V., Pelfini, M., 2024. *Development of the critical zone environment in the highly dynamic landscape of the Forni Glacier forefield: Winds, tree vegetation, pedogenesis and surface waters after glacier retreat*. Earth Surface Processes and Landforms, 49 (14), 4587-4609. https://doi.org/10.1002/esp.5983

Lewin J., Macklin M.G., 2003. *Preservation potential for late Quaternary River alluvium*. Quaternary Science Reviews, 22(18-19), 2193-2230. https://doi.org/10.1002/jqs.738

Locatelli A.M., Martinelli N., 2023. *Eating at the coaching inn: food culture and hospitality in the Central Alps from the 18th century to the present*. In: Eating on the Move, 75-90. Routledge, New York.

Longhi A., Monticelli D., Guglielmin M., 2020. *The use of iron chemical analysis of podzols to date the Late Pleistocene-Holocene deglaciation history of the Central Italian Alps*. Journal of Quaternary Science, 35 (8), 1021-1035. https://doi.org/10.1002/jqs.3253

Longhi A., Trombino L., Guglielmin M., 2021. *Soil micromorphology as tool for the past permafrost and paleoclimate reconstruction*. Catena, 207, 105628. https://doi.org/10.1016/j.catena.2021.105628

Louis C., Halloran L.J., Roques C., 2024. *Seasonal and diurnal freeze-thaw dynamics of a rock glacier and their impacts on mixing and solute transport*. EGUsphere, 2024, 1-26. https://doi.org/10.5194/egusphere-2024-927, 2024.

Malfasi F., Cannone N., 2020. *Climate warming persistence triggered tree ingression after shrub encroachment in a high alpine tundra*. Ecosystems, 23, 1657-1675. https://doi.org/10.1007/s10021-020-00495-7

Morosini, S., 2022. *"Following in the footsteps of history". Sixteen Multimedia Itineraries through the World War I sites in the Stelvio National Park and Adamello Park (Italy).* In: Svensson D., Saltzmann K., Sörlin S. (Eds), Pathways. Exploring the Routes of a Movement Heritage, 114-127. The White Horse Press, Cambridgeshire, UK.

Olvmo M., Johansson M., 2002. *The significance of rock structure, lithology and pre-glacial deep weathering for the shape of intermediate-scale glacial erosional landforms.* Earth Surface Processes and Landforms, 27 (6), 1-15. https://doi.org/10.1002/esp.317

Panizza M., 1996. *Environmental geomorphology.* Elsevier, Amsterdam, 267 pp.

Paul F., Rastner P., Azzoni R.S., Diolaiuti G., Fugazza D., Le Bris R., Smiraglia C., 2019. *Glacier shrinkage in the Alps continues unabated as revealed by a new glacier inventory from Sentinel-2.* Earth System Science Data Discussions, 2019, 1-28. https://doi.org/10.5194/essd-12-1805-2020, 2020

Pelfini M., Bollati I., 2014. *Landforms and geomorphosites ongoing changes: concepts and implications for geoheritage promotion*. Quaestiones Geographicae, 33 (1), 131-143.

Pelfini M., Carton A., Bozzoni M., Leonelli G., Martinoli M., Santilli M., 2009. *Enhancement of glacial and periglacial geomorphosites based on geomorphological and dendrochronological research. An example from the Trafoi Valley (Ortles-Cevedale Group).* Memorie Descrittive della Carta Geologica d'Italia, LXXXVII, 123-134.

Pelfini M., Diolaiuti G., Smiraglia C., 2004. *Proposte ed esempi di fruizione turistica dell'alta montagna glacializzata: metodi di indagine per la percezione dei beni geomorfologici e per la loro valorizzazione.* In: Adamo F. (Ed.), *Turismo e territorio in Italia*, 355-363.

Pelfini M., Diolaiuti G., Smiraglia C., 2005. *I ghiacciai come beni geomorfologici dell'alta montagna alpina: identificazione e valorizzazione.* In: Terranova R., Brandolini P., Firpo M. (Eds), La valorizzazione turistica dello spazio fisico come via alla salvaguardia ambientale, 345-368. Patron, Bologna.

Pelfini M., Santilli M., 2006. *Dendrogeomorphological analyses on exposed roots along two mountain hiking trails in the Central Italian Alps.* Geografiska Annaler, Series A: Physical Geography, 88 (3), 223-236. https://doi.org/10.1111/j.1468-0459.2006.00297.x

Pelfini M., Smiraglia C., 2003. *I ghiacciai, un bene geomorfologico in rapida evoluzione.* Bollettino Società Geografica Italiana, serie XI, 8, 521-544.

Pelfini, M., Leonelli, G., Trombino, L., Zerboni, A., Bollati, I., Merlini, A., Diolaiuti, G., 2014. *New data on glacier fluctuations during the climatic transition at ~4,000 cal. year BP from a buried log in the Forni Glacier forefield (Italian Alps).* Rendiconti Lincei, 25, 427-437. https://doi.org/10.1007/s12210-014-0346-5

Ponti S., Cannone N., Guglielmin M., 2018. *Needle ice formation, induced frost heave, and frost creep: a case study through photogrammetry at Stelvio Pass.* Catena, 164, 62-70. https://doi.org/10.1016/j.catena.2018.01.009

Regione Lombardia – Servizio Geologico (2001). *Carta geologica derivata dalla banca dati geologica 1:10.000, Progetto CARG. Sezione N. D1d4 Passo dello Stelvio.* Edizione 2001. Milano: Regione Lombardia, Direzione Generale Territorio e Urbanistica – Servizio Geologico. Scala 1:10.000.

Remondo J., Soto J., González-Díez A., de Terán J.R.D., Cendrero A., 2005. *Human impact on geomorphic processes and hazards in mountain areas in northern Spain.* Geomorphology, 66 (1-4), 69-84. https://doi.org/10.1016/j.geomorph.2004.09.009

Sannino C., Borruso L., Mezzasoma A., Battistel D., Ponti S., Turchetti B., Buzzini P., Guglielmin M., 2021. *Abiotic factors affecting the bacterial and fungal diversity of permafrost in a rock glacier in the Stelvio Pass (Italian Central Alps).* Applied Soil Ecology, 166, 104079. https://doi.org/10.1016/j.apsoil.2021.104079

Schrott L., Sass O., 2008. *Application of field geophysics in geomorphology: advances and limitations exemplified by case studies.* Geomorphology, 93, 55-73. https://doi.org/10.1016/j.geomorph.2006.12.024

Shoshitaishvili B., 2021. *From Anthropocene to noosphere: the great acceleration.* Earth's Future, 9 (2). https://doi.org/10.1029/2020EF001917

Società Economica Valtellinese, 2021. *Donegani, l'ingegnere tra le Alpi. La sfida al Giogo di Stelvio.* Tipografia Bettini, Sondrio, 176 pp.

Slaymaker O., Kelly R., Tate N. (Eds), 2009. *The cryosphere and global environmental change.* Wiley-Blackwell.

Smiraglia C., Diolaiuti G., Pelfini M., 2015. *Trasformazioni del paesaggio glaciale dell'alta montagna: riduzione o evoluzione della geodiversità?* In: D'Andrea M., Rossi R. (Eds), *Geologia e Turismo … a 10 anni dalla fondazione. 5° Congresso Nazionale Geologia e Turismo*, 60-70. ISPRA.

Steffen W., 2021. *The Earth system, the great acceleration and the Anthropocene.* In: *Sustainability and the new economics: synthesising ecological economics and modern monetary theory*, 15-32. Springer International Publishing, Cham.

Vitalini S., Puricelli C., Mikerezi I., Iriti M., 2015. *Plants, people and traditions: ethnobotanical survey in the Lombard Stelvio National Park and neighbouring areas (Central Alps, Italy).* Journal of Ethnopharmacology, 173, 435-458. https://doi.org/10.1016/j.jep.2015.05.036

(Ms. received 12 May 2025, accepted 23 September 2025)