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# The challenges of the "ephemeral path". Problems and issues of explaining climate change and its environmental impact through the development of glaciological trails

**Abstract:** Smiraglia C., Senese A., Di Biase M., Ambrosini R., Azzoni R.S., Bocchiola D., Cola G., Favaron M., Fugazza D., Marzano D., Morosini S., Pedrotti L., Prandi G., Scotti R., Toffaletti A., Zucali M., Pelfini M., Diolaiuti G.A., *The challenges of the "ephemeral path". Problems and issues of explaining climate change and its environmental impact through the development of glaciological trails.* (IT ISSN 0391-9838, 2026). Global warming is profoundly transforming glacierized mountain landscapes, with significant consequences for the environment, safety, and tourism. In this context, scientific outreach and conscious engagement with the territory are essential to raise public awareness and promote sustainable behaviour. This paper presents the design and implementation of the Stoppani-Desio Glaciological Trail, an educational route developed to guide visitors through the ongoing transformations of the Forni Glacier, located within Stelvio National Park (Italy). The trail features thirteen observation points, each corresponding to a historical position of the glacier front over the past 3000 years. At each stop, a metal plaque equipped with a QR code provides access to multilingual digital content (texts, images, and videos) highlighting glaciological, ecological, and cultural aspects of the site. The signage is designed to be durable, inclusive, and low-impact, while the trail ensures safety and accessibility for users with varying physical and technical abilities. The project integrates scientific research, landscape interpretation, and digital tools (e.g., 360° video and generative AI content), positioning the trail as a dynamic open-air laboratory. The initiative is supported by a collaborative governance model involving academic institutions, local authorities, Alpine guides, and volunteers, enabling regular updates and long-term maintenance. The Stoppani-Desio Trail offers a replicable model for glaciological trails in other mountain regions affected by glacier retreat. Its flexible infrastructure, multilingual outreach, and integration of real-time scientific data make it a promising strategy for combining sustainable tourism, environmental education, and the promotion of glacier heritage in a changing climate.

**Key words:** Glaciological trails, Climate change, Environmental impacts, Glacier shrinkage, Forni Glacier.

**Riassunto:** Smiraglia C., Senese A., Di Biase M., Ambrosini R., Azzoni R.S., Bocchiola D., Cola G., Favaron M., Fugazza D., Marzano D., Morosini S., Pedrotti L., Prandi G., Scotti R., Toffaletti A., Zucali M., Pelfini M., Diolaiuti G.A., *Le sfide del "percorso effimero". Problemi e questioni legati alla spiegazione dei cambiamenti climatici e del loro impatto ambientale attraverso lo sviluppo di percorsi glaciologici.* (IT ISSN 0391-9838, 2026). Il riscaldamento globale sta trasformando profondamente i paesaggi montani glaciali, con conseguenze significative per l'ambiente, la sicurezza e il turismo. In questo contesto, la divulgazione scientifica e l'impegno consapevole con il territorio sono strumenti essenziali per sensibilizzare l'opinione pubblica e promuovere comportamenti sostenibili. Questo articolo presenta la progettazione e la realizzazione del Sentiero Glaciologico Stoppani-Desio, un percorso didattico sviluppato per guidare i visitatori attraverso le trasformazioni in atto del Ghiacciaio dei Forni, situato all'interno del Parco Nazionale dello Stelvio (Italia). Il percorso presenta tredici punti di osservazione, ciascuno dei quali corrisponde a una posizione storica del fronte del ghiacciaio negli ultimi 3000 anni. In ogni punto, i visitatori trovano una targa metallica con un codice QR che dà accesso a contenuti multilingue (testi, immagini, video) che mettono in evidenza gli aspetti glaciologici, naturalistici e culturali del sito. La segnaletica è progettata per essere accessibile, adattabile e a basso impatto, mentre il percorso è strutturato in modo da garantire sicurezza e inclusività, adattandosi a utenti con diversi livelli di abilità e capacità fisiche e tecniche. Il progetto integra ricerca scientifica, lettura e interpretazione del paesaggio e strumenti digitali (ad esempio, video a 360° e contenuti generati con Intelligenza Artificiale Generativa-GAI), posizionando il sentiero come un laboratorio dinamico a cielo aperto. L'iniziativa è supportata da un modello di governance collaborativa che coinvolge istituzioni accademiche, autorità locali, guide alpine e volontari, consentendo aggiornamenti regolari e manutenzione a lungo termine. Il Sentiero Stoppani-Desio offre un modello replicabile per percorsi glaciologici in altre regioni montane interessate dal ritiro dei ghiacciai. La sua infrastruttura flessibile, la comunicazione multilingue e l'integrazione di dati scientifici in tempo reale lo rendono una strategia promettente per combinare turismo sostenibile, educazione ambientale e valorizzazione del patrimonio glaciale in un contesto di cambiamento climatico.

**Termini chiave:** Sentieri glaciologici, Cambiamenti climatici, Impatto ambientale, Riduzione dei ghiacciai, Ghiacciaio dei Forni.

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## INTRODUCTION

Glacierized mountain regions are undergoing rapid and unprecedented transformations due to climate change, with cascading impacts on geomorphological stability, hydrology, safety, tourism, and heritage (Zemp *et al.*, 2015; Huss and Hock, 2018; Paul *et al.*, 2020). In the European Alps, long-term warming and mass loss have driven continuous retreat since the Little Ice Age, with smaller glaciers approaching disappearance within decades, raising urgent concerns for risk management and public awareness (Shannon *et al.*, 2019; Reinthaler and Paul, 2025).

In this evolving context, glaciological trails have emerged as accessible educational routes that couple direct observation with landscape interpretation, offering a concrete medium to communicate climate-change impacts, paraglacial dynamics, and ecosystem responses to diverse audiences. Across the Alps and beyond, several initiatives illustrate the potential of interpretive infrastructure and curated content: from the Morteratsch Glacier Trail in Switzerland – historically celebrated for its easy access but now documenting increasing difficulty as the terminus retreats (Maisch *et al.*, 1993) – to broader surveys of interpretive practices, geotourism resources, and glacier tourism sites (Cayla, 2009; Perotti *et al.*, 2020; Salim *et al.*, 2021). In Italy, approximately ten official trails exist, with a wider set of itineraries documented by national guides (CGI, 2017), though the visibility and open-access dissemination of many routes remain limited.

Designing and maintaining glaciological trails today entails a key challenge: ensuring safety, inclusivity, and scientific value amid fast-changing alpine terrains. Retreating termini, evolving proglacial plains, moraine instability, and changing stream paths can compromise access and signage within short timescales, requiring adaptive routing and regularly updated interpretive materials. At the same time, visitor profiles have diversified – from expert hikers to families and people with reduced mobility – making clarity of risk communication and logistical information essential.

This paper presents the Stoppani-Desio Glaciological Trail at the Forni Glacier (Stelvio National Park, Italy, fig. 1) as a replicable model that integrates: (i) adaptive trail design with minimal environmental impact by prioritizing pre-existing paths; (ii) inclusive access with modular, low-impact signage; and (iii) hybrid communication via multilingual QR codes linked to a centrally managed digital platform. The trail comprises thirteen observation points aligned with historical glacier positions over the last ~3000 years, each associated with concise site-specific content (texts, images, audio/video) on glaciological, ecological, and cultural features. Thanks to long-term research in the Forni Valley (e.g., hydrological monitoring network, supraglacial AWS, and UAV-based surveys), the trail also functions as an open-air laboratory that connects visitors with ongoing scientific measurements and hazard awareness.

The study aims are threefold: (1) to document a practical, low-impact approach for conceiving, designing, and implementing a glaciological trail under rapid environmental change; (2) to situate the methodology within the broader Alpine and international landscape of glaciological interpretation and geotourism; and (3) to discuss replicability, governance, and communication strategies that sustain the educational value of trails while accommodating environmental dynamics and diverse user needs.

## STUDY AREA: THE FORNI GLACIER AS AN OPEN-AIR LABORATORY

The Forni Glacier (46° 23′ 53.52″ N, 10° 35′ 17.16″ E) is one of the largest glaciers in Lombardy (10.5 km$^2$, data of 2016, Paul *et al.*, 2020), located in the Central Italian Alps (fig. 1). It is included in the official list of geosites of the Province of Sondrio (Regione Lombardia, 2008) and has been extensively studied for its geoheritage value (Diolaiuti and Smiraglia, 2010). The glacier is about 3 km long, has a northward down-sloping surface, and stretches over an elevation range of about 2600 to 3670 m a.s.l.

The glacier also serves as a striking example of how climate change is reshaping glacier tourism. Over the past few decades, the Forni Glacier has undergone significant shrinkage: it has retreated by approximately 2.5 km in length over the last 150 years (fig. 2) and lost more than 50 m in thickness in the past 50 years (CGI, 1928-1977; CGI, 1978-2021; Diolaiuti and Smiraglia, 2010; Fugazza *et al.*, 2018; Baroni *et al.*, 2022; 2023; Chiarle *et al.*, 2024a; 2024b).

This has affected not only the visual and recreational appeal of the glacier and the tourist perception of climate change effects, but also the safety of visitors. As the glacier retreats, previously stable ice formations become increasingly unstable (Riccardi *et al.*, 2010). For example, the growing instability of the Forni Glacier terminus has rendered certain sections too dangerous for tourists, leading to the rerouting of trekking paths and restricted access to areas that were once popular for hiking and climbing. On the Forni Glacier, repeated drone-based monitoring has enabled the mapping of crevasses on the ablation tongue and the analysis of their intra- and inter-annual evolution (Fugazza *et al.*, 2018). A particularly interesting application of UAVs (Unmanned Aerial Vehicles) has been the study of ring crevasses. These features form in areas where the glacier changes direction, causing the outer edge of the ice to move faster than the inner edge. This speed differential generates tensile stress, which fractures the ice and creates crevasses that radiate outward from the inner corner of the bend, forming a distinctive “ring” or “fan-shaped” pattern. The evolution of ring crevasses is a dynamic process, influenced by glacier flow and stress field variations. Over time, they may close or heal as they are advected (transported) downstream to other

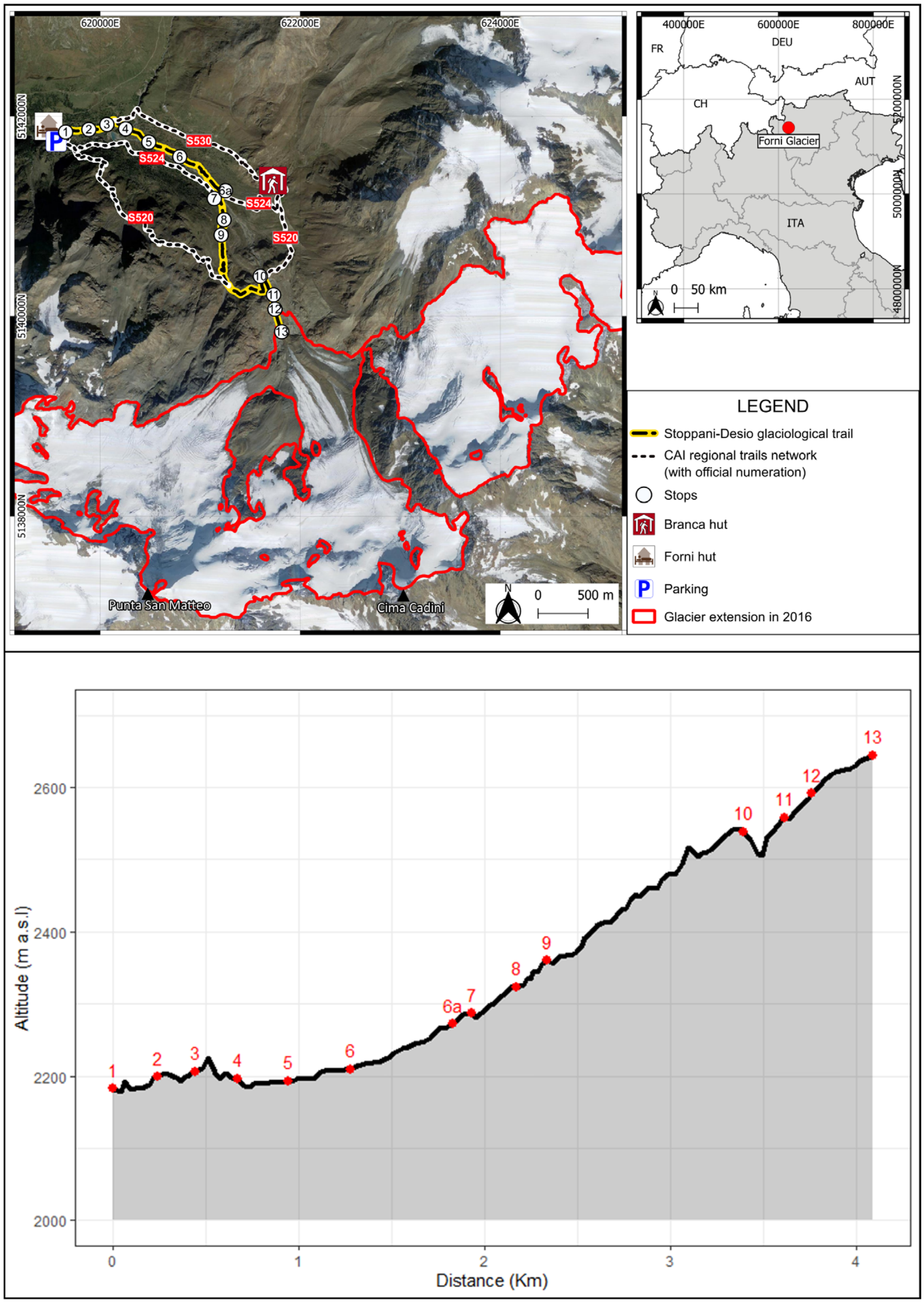


Figure 1 - The Stoppani-Desio trail to Forni Glacier. The base raster is a colour orthophoto (courtesy Lombardy Region). In lower panel the elevation profile with the 13 official stops is shown.

parts of the glacier (Colgan *et al.*, 2016). In the case of ring crevasses, it has been observed that these features can act as precursors of cavity formation, resulting from the collapse of glacier sections bounded by such fractures (Azzoni *et al.*, 2017). This highlights the value of UAV-based monitoring, which can support local authorities in managing access to glacier areas undergoing rapid change and subject to high environmental hazard and risk levels, already evident nearly two decades ago (Azzoni *et al.*, 2017).

The Forni Valley is also monitored as part of the Idrostelvio Project (Bocchiola *et al.*, 2025). Launched in 2010, Idrostelvio is a long-term collaboration between the Stelvio National Park, the University of Milan, and the Polytechnic University of Milan. It has established the largest and longest-running hydrological monitoring network in glacierized areas in Italy, encompassing 11 high-altitude glacier-fed streams. The project makes a significant contribution to glacio-hydrology, providing valuable datasets for scientific research, model calibration, and educational purposes. Its monitoring system covers approximately 32% of the park's area and over 90% of its glacierized zones, offering a detailed understanding of alpine hydrological processes. In the Forni Valley, two hydrological stations have been installed, enabling the collection of continuous meltwater runoff data (fig. 3).

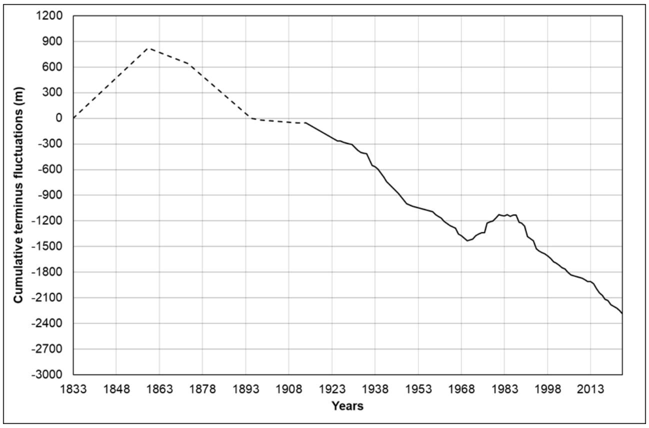


Figure 2 - Cumulative terminus fluctuations of the Forni Glacier from 1833 to 2024. Data are sparse and discontinuous in the earlier part of the record (dashed line), while from the early 20th century onwards, measurements have been conducted systematically and annually (solid line), thanks to the long-term monitoring efforts of volunteers from the Italian Glaciological Committee and the Lombardy Glaciological Service.

Figure 3 - A footbridge along the glaciological trail in the Forni Valley, equipped with a radar sensor for monitoring streamflow. The monitored stream is the main outlet river, fed by ice and snow melt from the Forni Glacier.

Regarding forest dynamics and vegetation recolonization of areas exposed by glacier retreat, Garavaglia *et al.* (2010) estimated the ecesis time of Larix decidua Mill. and Pinus cembra, based on the glacier front position in 1998. Their results showed a progressive decrease in recolonization time from the end of the Little Ice Age to the late 20th century (fig. 4).

Since 2005, an Automatic Weather Station (AWS) has been operating on the surface of the ablation tongue of the Forni Glacier (e.g. Senese *et al.*, 2012; 2014; Gambelli *et al.*, 2014), continuously collecting meteorological and radiative data; in 2014 under the umbrella of the WMO SPICE project a second AWS was installed close to the first one, thus completing the meteorological observation strategy of the Forni Glacier (fig. 5). These observations are crucial for modelling glacier melt (Senese *et al.*, 2018) and for providing input data (e.g., air temperature, wind speed, incoming shortwave and longwave radiation) to spatially distribute glacier ablation using physically based energy balance models or empirical melt models (Senese *et al.*, 2016, 2020, 2021). To calibrate and validate melt models at the glacier surface, ablation stakes are also used. These are 2-meter-long bamboo stakes, inserted into the glacier by drilling with a manual auger. Their seasonal emergence is measured by volunteers and researchers, providing direct estimates of summer ice loss and enabling cross-checks with melt model outputs. The AWS is also equipped with a net radiometer that measures incoming and reflected shortwave radiation, allowing the estimation of glacier surface albedo and supporting the validation of satellite-derived albedo maps (see Fugazza *et al.*, 2016). Thanks to these measurements, it was possible to confirm the glacier darkening phenomenon in the Alps (Fugazza *et al.*, 2019).

Finally, the Forni Glacier was the first site where microplastic (MP) contamination was identified in 2017 (Ambrosini *et al.*, 2018). In addition to contamination on glacier surfaces, macroplastic debris has also been quantified along trails leading to glacial areas, including at the Forni Glacier itself, highlighting that both the glacier and its access routes are becoming zones of plastic accumulation (Litholdo *et al.*, 2025). During the same period, ecologists also extensively investigated the microbial communities and fauna inhabiting supraglacial environments, identifying the structure of their ecological networks (Crosta *et al.*, 2024) as well as the spatial and temporal variation of these communities (e.g., Novotná Jaroměřská *et al.*, 2025).

The Forni Glacier is also an important historical open-air archive. Due to the progressive melting and thinning of the ice, artefacts once entrapped within the glacier are now emerging at the surface, particularly during the summer melt season. These include relics from the First World War (1915-1918), highlighting how anthropogenic impacts on glaciers have deep historical roots. In addition to objects related to the former military garrison (e.g., barracks, stoves, clothing, utensils), weapons-related debris such as mines, bombs, ammunition, barbed wire, and fragments of firearms have also been found at the glacier surface. If such artefacts are encountered, it is essen-

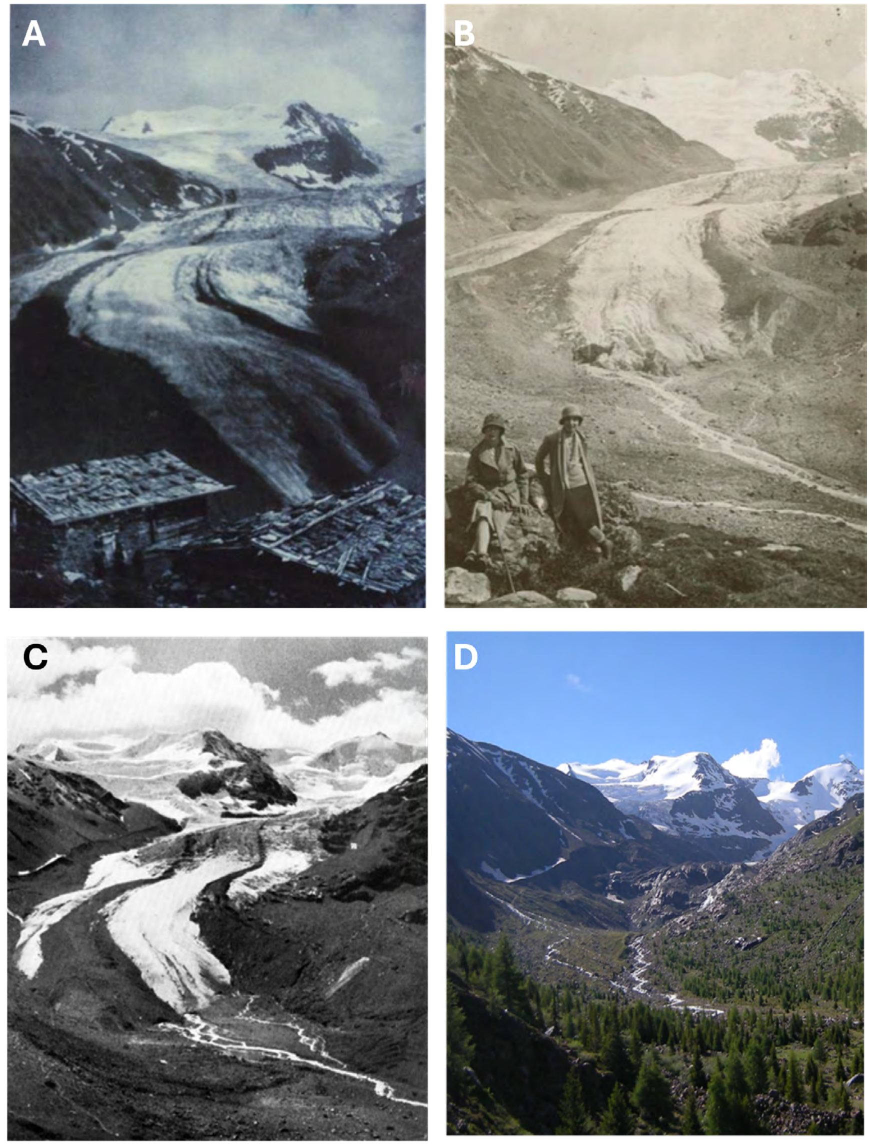


Figure 4 - Historical and modern photographs illustrating glacier retreat and subsequent forest recolonisation. A) Photo by V. Sella (late 19th century), showing the glacier with a prominent ice tongue reaching the valley floor. B) Early 20th-century photo from P. Casati's archive, documenting initial retreat. C) Photo by A. Desio, showing a significantly shortened ice tongue. D) Recent image by C. Smiraglia (21st century), where the glacier tongue has disappeared and the valley has been colonized by larch and pine forest over more than 2.5 km of deglaciated terrain.

tial not to touch or remove them, and to promptly report the finding to the competent authorities (in this case, the Stelvio National Park and the Carabinieri Forestry Corps) providing photographs of the object in situ along with its GPS coordinates (fig. 6). Unexploded ammunition is extremely dangerous and must be neutralized by professionals. In contrast, historical artefacts deemed safe are often entrusted to local museums for preservation and display (Morosini, 2022).

For all these reasons, the Forni Glacier attracts thousands of hikers every year, with several hundred also venturing onto its surface to observe its evolving morphology, visit scientific monitoring equipment, or search for historical remains. An updated and well-designed trail is therefore essential to guide these growing tourist flows and to ensure visitor safety, in particular through appropriate signage and clear behavioral guidelines.

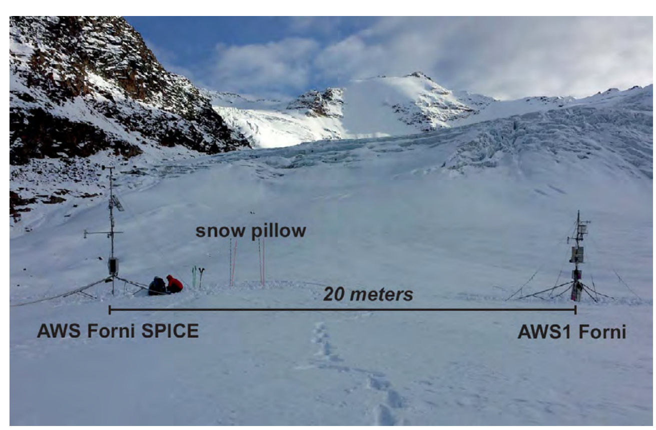


Figure 5 - The two Automatic Weather Stations (AWS1 Forni and AWS Forni SPICE), installed on the ablation tongue of the Forni Glacier. These stations are part of several monitoring programmes developed under the coordination of the World Meteorological Organization (WMO), including the SPICE project and the OSCAR network.

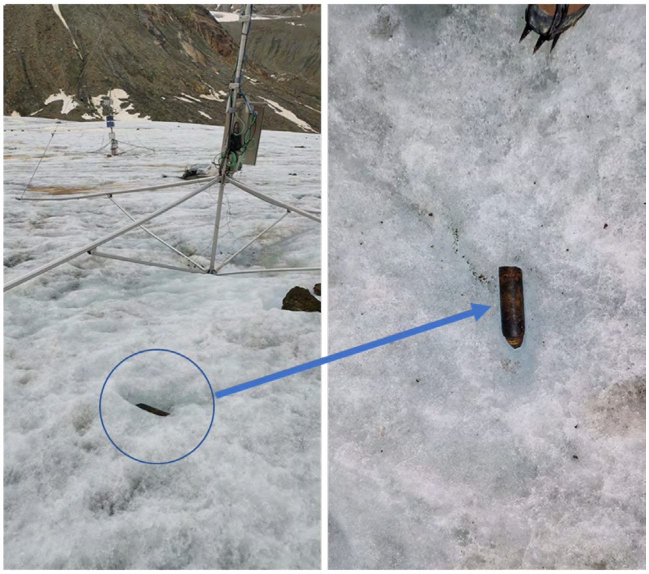

Figure 6 - Unexploded ordnance that surfaced from the ice near the AWS on the Forni Glacier. The location of the find was reported by scientists to the Carabinieri Forestry Corps, who coordinated the safe removal and controlled detonation of the device at a secure site.

## METHODS: PROJECT STRATEGY

### *The former glaciological trails to view and visit the Forni Glacier*

The Forni Glacier Glaciological Trail was developed as a replacement for an earlier route that had become largely impractical due to significant environmental and landscape changes over recent decades. The original trail was established in 1995 by the Italian Glaciological Committee, the University of Milan, and the Italian Alpine Club (CAI). Named the Centenary Trail, it was created to commemorate the 100$^{th}$ anniversary of the CAI Glaciological Commission (which later became the Italian Glaciological Committee, now the Italian Glaciological Foundation ETS). The trail was immediately successful and widely used by tourists and hikers. This loop trail allowed visitors to reach the glacier surface, cross it, and return to the valley along a different route. However, only a few years after its inauguration, the trail required multiple reroutings due to repeated collapses of ice-cored moraines, mudflows and debris flows, and the retreat of the glacier terminus by over 600 m. By 2005, the trail no longer provided direct access to the glacier. In response, local mountain guides and CAI branches proposed two alternative variants (i.e. known as the "high" and "low" glaciological trails) both ending at the glacier's forehead. Unfortunately, the terminus area had become increasingly hazardous, affected by collapsing debris and unstable sediments comparable to quicksand.

This historical trail was later included as Itinerary No. 15 in the *Guide Geologiche Regionali – Itinerari glaciologici sulle montagne italiane* (CGI, 2017), where it is described in detail for its scientific, didactic, and historical significance. The loop path, starting and ending at the Forni Hut, was one of the first examples of a glaciological itinerary designed not only to showcase the glacier's morphology but also to promote climate change awareness and the cultural legacy of glaciology in the Italian Alps. The guide emphasizes the relevance of this site through multiple observation stops (e.g. moraines, bedrock polish, proglacial vegetation) framing it as a paradigmatic case of glacier retreat and landscape transformation. However, despite its inclusion in this national overview, the trail has undergone substantial changes and can no longer be used in its original form due to ongoing glacier shrinkage and slope instability. In fact, since 2015, collapses in the large Little Ice Age moraine on the glacier's hydrographic right have become more frequent. This section now requires increased caution, especially following intense rainfall, yet many hikers remain unaware of the associated risks. At the same time, the profile of glacier visitors has changed significantly, with an increasing number of bikers riding near crevasses and moulins, often unaware of the dangers. Families with children have also increased, often lacking appropriate footwear or safety equipment such as ropes and harnesses, despite venturing onto glacier ice.

### *The Stoppani-Desio trail*

The "Sentiero Stoppani-Desio al Ghiacciaio dei Forni" (Stoppani-Desio Trail to the Forni Glacier) was developed to meet the need for a safe and educational route allowing visitors to admire both the glacier and the surrounding Forni Valley. The trail also celebrates 2025 as the International Year of Glacier Preservation (see www.un-glaciers.org) by dedicating the itinerary to two key figures in Italian glaciology: Antonio Stoppani and Ardito Desio.

To develop this new trail, an ad hoc working group was established with the dual goal of designing an optimal, low-impact route and promoting its use through educational and tourism initiatives. The group includes: i) glaciological experts from universities (University of Milan, University of Bergamo) and national/regional associations (Italian Glaciological Committee – CGI, Lombardy Glaciological Service – SGL), ii) representatives of local institutions promoting sustainable tourism (Municipality of Valfurva, Stelvio National Park Authority – ERSAF), iii) volunteers from mountaineering associations (e.g. the Valfurva section of the Club Alpino Italiano – CAI), and iv) professionals in mountain tourism (e.g. alpine guides, mountain leaders).

The planning process started from the group's deep, long-standing knowledge of the area, with a careful analysis of existing trails to reuse pre-existing paths where possible, thus reducing the environmental impact on this


Figure 7 - One of the thirteen trail plaques installed on-site. Each plaque indicates the stop's location relative to the full trail and includes QR codes that give access to multimedia content explaining the site's geological or historical relevance.

fragile high-altitude landscape. New segments were proposed only where strictly necessary. In areas where former paths were missing or degraded, extraordinary maintenance work was planned, including connecting sections between viable portions. A notable example is the replacement of the footbridge over the glacier-fed stream in the middle of the Forni Valley (fig. 3). The original bridge was destroyed during the October 2023 flood event, making access unsafe for hikers. In 2024, the Stelvio National Park Authority (ERSAF) installed a new, solid wooden bridge to restore safe passage. Additionally, this new infrastructure hosts permanent scientific instrumentation to monitor meltwater runoff, further integrating this site into the open-air laboratory of the Forni Glacier (Bocchiola *et al.*, 2025).

Through extensive field surveys, glaciologists identified 13 observation points (tab. 1), each corresponding to a known position of the glacier terminus over the past 3,000 years. These stops form the basis of the new glaciological trail. To guide and inform hikers, each stop is marked with a metal plaque, either fixed to rock or mounted on a wooden stake. Each plaque includes (fig. 7): i) the trail's name and stop number (1 to 13), ii) a date label (either "Before Present – BP" or "Anno Domini – AD") representing when the glacier reached that point, iii) a "You are here" map showing the hiker's position along the trail, and iv) a QR code providing access to multilingual multimedia content (text, images, audio in Italian, English, and German) specific to that location.

The QR codes are unique for each plaque and lead to site-specific content. Each multimedia page includes not only local insights but also the trail map, enabling users to orient themselves and plan their remaining route. Furthermore, each stop is introduced with a short thematic subtitle, highlighting a geological, ecological or cultural feature visible from that point.

To maximize visibility, the full trail overview map and summary panel (fig. 8) are displayed in three key locations: i) a lower parking area at 1725 m a.s.l., located near the last inhabited hamlet of Valfurva, from where electric shuttle buses depart in summer to reduce environmental impact, ii) a higher parking lot at around 2100 m a.s.l., used by visitors with special access needs (e.g. transporting equipment or people with reduced mobility), a daily fee is required here, and iii) inside the two main mountain huts in the valley: Rifugio Albergo dei Forni (2100 m a.s.l.) and Rifugio Cesare Branca (2493 m a.s.l.), where the panel is also displayed in poster format for hikers.

The overview panel is presented in three languages (i.e. Italian, English, and German) and provides only the essential information needed to decide whether to undertake the trail. This multilingual approach reflects the high number of international visitors to the Forni Glacier area, one of the most well-known and frequently visited glaciers in Italy. Unfortunately, most nature trails in Italy offer information only in Italian, limiting accessibility and understanding for foreign tourists. In our project, we retained Italian as the local language, added English for the international public, and included German due to the specific geographical and linguistic context of the Stelvio National Park, which spans three regions: Lombardy (where the Forni Glacier is located), the Autonomous Province of Trento, and the Autonomous Province of Bolzano. In the latter two, German is widely spoken, and thus providing the trail's educational and scientific content in German was deemed appropriate and inclusive.

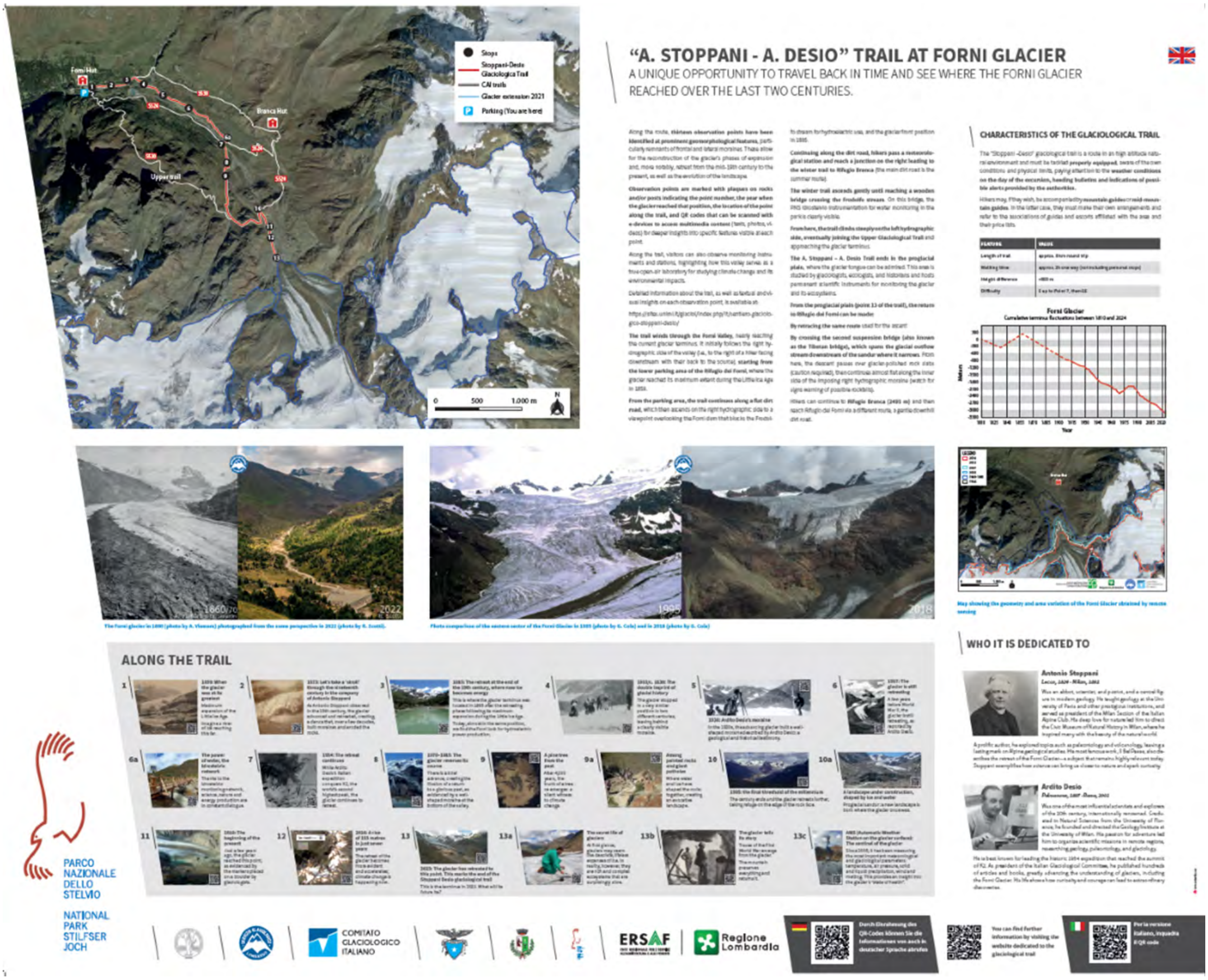


Figure 8 - Overview panel of the Stoppani-Desio Glaciological Trail at the Forni Glacier. The panel provides a clear and accessible representation of the full itinerary and includes QR codes that offer access to in-depth multimedia content for visitors seeking additional information.

The panel includes key information such as total trail length, general features and difficulty, estimated walking time, number and location of observation stops, a large colour orthophoto map of the valley (based on data from the Regione Lombardia Geoportal), and for each stop, a ground photograph with a short caption describing a relevant natural, geological, or cultural feature, along with a QR code giving access to multilingual multimedia content.

All QR codes direct users to a dedicated web platform hosted on a project partner's server (https://sites.unimi.it/glaciol/index.php/it/sentiero-glaciologico-stoppani-desio/) and are also accessible via the official websites of all institutional partners. This approach allows for centralised updates: any modifications (e.g. due to landscape changes, new hazards, or trail rerouting) can be made on a single platform, automatically updating all linked sites and digital materials.

## RESULTS

The whole path is reported in fig. 1. To enhance the readability and thematic structure of the trail, tab. 1 summarizes the stop numbers, along with their corresponding titles and subtitles. Each stop is designed to highlight a key aspect of glacier history, landscape evolution, or climate change, offering visitors a narrative journey through time along the Forni Glacier trail.

The Stoppani-Desio Glaciological Trail is located in a high-altitude natural environment and should be undertaken with appropriate equipment and full awareness of one's physical condition and limitations. Hikers are advised to check weather conditions on the day of the excursion and follow any bulletins or alerts issued by the relevant authorities. Where appropriate, hikers may be accompanied by certified mountain guides or leaders. The main structural

Table 1 - Overview of the 13 official stops (and thematic sub-stops) along the Stoppani-Desio Glaciological Trail. Each stop is associated with a specific historical or scientific theme, represented by a title and subtitle, to guide visitors through the recent evolution of the Forni Glacier and its surrounding landscape.

| Stop N. | Title | Subtitle (short description) |
|---|---|---|
| 1 | 1859: When the glacier was at its greatest | Maximum expansion of the Little Ice Age. Imagine a river of ice reaching this far. |
| 2 | 1873: Let's take a 'stroll' through the nineteenth century in the company of Antonio Stoppani | As Antonio Stoppani observed in the 19th century, the glacier advanced and retreated, creating a dance that, over a few decades, built moraines and locally reworked the valley floor. |
| 3 | 1885: The retreat at the end of the 19th century, where now ice becomes energy | This is where the glacier terminus was located in 1885 after the retreating phase following its maximum expansion during the Little Ice Age. Today, almost in the same position, we find the Forni lock for hydroelectric power production. |
| 4 | c. 1903 /c. 1830: The double imprint of glacial history | The glacier stopped in a very similar position in two different centuries, leaving behind a clearly visible moraine. |
| 5 | 1926: Ardito Desio's moraine | In the 1920s, the advancing glacier built a well-shaped moraine described by Ardito Desio: a geological and historical testimony. |
| 6 | 1937: The glacier is still retreating | A few years before World War II, the glacier is still retreating, as reported by Ardito Desio. |
| 6a | The power of water, the Idrostelvio network | Thanks to the Idrostelvio monitoring network, science, nature and energy production are in constant dialogue. |
| 7 | 1954: The retreat continues | While Ardito Desio's Italian expedition conquers K2, the world's second highest peak, the glacier continues to retreat. |
| 8 | 1970-1985: The glacier reverses its course | There is a brief advance, creating the illusion of a return to a glorious past, as evidenced by a well-shaped moraine at the bottom of the valley. |
| 9 | A stone Pine tree from the past | After 4,000 years, the trunk of a tree re-emerges: a silent witness to climate change. |
| 9a | Among painted rocks and giant potholes | Where water and ice have shaped the rocks together, creating an evocative landscape. |
| 10 | 1995: The final threshold of the millennium | The century ends and the glacier retreats further, taking refuge on the edge of the rock face. |
| 10a | A landscape under construction, shaped by ice and water | Proglacial *sandur*: a new landscape is born where the glacier once was. |
| 11 | 2010: The beginning of the present | Just a few years ago, the glacier reached this point, as evidenced by the markers placed on a boulder by glaciologists. |
| 12 | 2016: A rise of 183 metres in just seven years | The retreat of the glacier becomes more evident and accelerates; climate change is happening now. |
| 13 | 2023: The glacier has retreated to this point – This marks the end of the Stoppani Desio glaciological trail | This is the terminus in 2023. What will its future be? |
| 13a | The secret life of glaciers | At first glance, glaciers may seem like desolate, lifeless expanses of ice. In reality, however, they are rich and complex ecosystems that are surprisingly alive. |
| 13b | The glacier tells its story | Traces of the First World War emerge from the glacier. The mountain preserves everything and returns it. |
| 13c | AWS (Automatic Weather Station on the glacier surface): The sentinel of the glacier | Since 2005, it has been measuring the most important meteorological and glaciological parameters: temperature, air pressure, solid and liquid precipitation, wind and melting. This provides an insight into the glacier's "state of health". |

Table 2 - The main characteristics of the glaciological trail.

| Feature | Value |
|---|---|
| Length of trail | approx. 8 km round trip |
| Walking time | approx. 2h one way (not including personal stops) |
| Height difference | approx. 600 m |
| Difficulty | E (Hiker trail) up to Point 7, then EE (Expert Hiker trail) |
| Suggested period of visit | Summer |
| Altitude of the starting point | 2140 m a.s.l. |
| Altitude of the highest reached point | approx. 2600 m a.s.l. |

features of the trail (e.g. elevation gain, total length, and estimated walking time) are reported in tab. 2 to provide a comprehensive framework for interpreting the glaciological and environmental data presented along the route. The difficulty levels reported follow the official CAI classification, where E indicates a hiking route and EE a trail for expert hikers.

Along the trail, some glacier terminus positions are reconstructed based on dated moraines that mark phases of glacier standstill or minor advances. Others are inferred from historical sources, such as maps, sketches, and photographs.

In the lower part of the valley (between the parking area and the confluence with the Cedech stream), visitors can visualize both the glacier advancing phase during the Little Ice Age (LIA) and some frontal terminus positions reached during both glacier advancing end retreating phases after LIA. This helps explain the apparent chronological discontinuity of the labelled stops and dates along the initial section of the trail.

The "A. Stoppani - A. Desio" Glaciological Trail follows the Forni Valley up to the current terminus of the glacier. The route develops along the hydrographic right side of the valley (i.e. to the right of hikers facing downstream with their backs to the glacier source) starting from the lower parking area near the Rifugio Albergo dei Forni, closed to area where the glacier reached its maximum extent during the Little Ice Age in 1859 (Stop 1, Omboni, 1861). A short detour across the glacial stream allows visitors to view a pair of adjacent frontal moraines that mark both the Holocene maximum extent (~2700 years BP, Orombelli and Pelfini, 1985) and the Little Ice Age maximum. These two distinct glacier advances culminated at nearly the same position in the valley. Between these two maxima, little geomorphological evidence remains in the main valley floor, likely removed by subsequent advances, although some older lateral moraines are still visible (Pelfini, 1992).

Following the Holocene maximum, the glacier underwent a long retreat (likely extending throughout the Medieval Warm Period) before re-advancing during the Little Ice Age. After reaching its LIA maximum in 1859, the Forni Glacier entered a retreat phase that continued until 1898 (Mariani, 1912). Historical records and mapping suggest a brief standstill around 1873, approximately 180 metres up-valley from the 1859 position, as described by Stoppani. This corresponds roughly to Stop 2 and is supported by IGM cartography and other historical documents.

From there, the trail continues along a gently climbing dirt road, arriving at a clearing near the estimated position reached by the glacier in 1885 (Stop 3), as reconstructed from IGM 1:25,000 topographic maps. From this point, a hydraulic lock is visible: it diverts part of the Frodolfo stream's flow into the hydroelectric network (fig. 9a).

The trail continues along the dirt road, passing by a weather station and reaching a junction that separates the summer route (main road) from the winter trail leading to

Figure 9 - Key sites along the Stoppani-Desio Glaciological Trail. (A) The Forni hydraulic lock, part of the Upper Valtellina hydroelectric system. (B) Rocks plates smoothed by glacier erosion near Stop 9A. (C) Oblique aerial view of the proglacial sandur taken by UAV during summer 2025. (D) The Tibetan bridge crossing the Forni stream on the return route.

Rifugio Branca. Before the confluence of two streams (i.e. the Cedech and the larger Frodolfo), a small bridge allows the crossing. On this bridge, hikers can clearly observe part of the Idrostelvio monitoring network to monitor water discharge in eleven glacier-fed streams across the park (Bocchiola *et al.*, 2025).

On the opposite bank, Stop 4 allows to observe the location where two glacier fronts are inferred: one from 1833 and another from the early 1900s, based on geomorphological and historical evidence (Mariani, 1912). Continuing at roughly the same elevation, hikers encounter the 1926 frontal moraine described by Ardito Desio (Stop 5), followed by the location of the 1937 glacier terminus (Stop 6, Desio, 1967). The road ascends slightly to another bridge over the Frodolfo stream, where further Idrostelvio instrumentation is also visible (fig. 3). The trail then crosses to the left hydrographic side of the valley and leads to the position reached by the glacier in 1954 (Stop 7, data from ortophoto Istituto Geografico Militare).

Just beyond, the path climbs more steeply in switchbacks along a small stream. Below, in the main valley floor, hikers can observe a series of well-preserved latero-frontal moraines at the base of a smooth rocky slope, evidence of a brief glacier advance between 1970 and 1985 (Stop 8).

Halfway up the rocky slope, the 1964 terminus position (prior to the 1970s advance) is also visible. The path continues with sharp hairpin bends on the same valley side, reaching approximately 2400 m a.s.l., where a log of stone pine (*Pinus cembra L.*) was found buried in moraine deposits, having been preserved for over 4000 years (Stop 9, fig. 10; see Pelfini *et al.*, 2014).

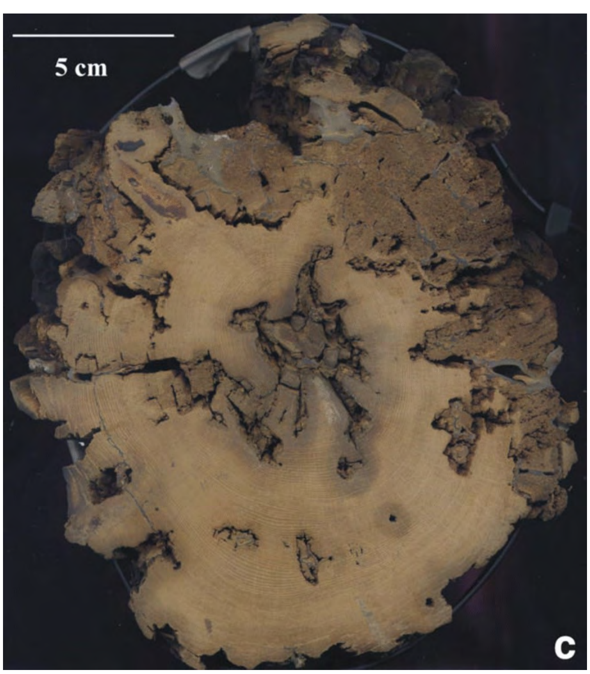

Figure 10 - Section of a 4000-year-old tree trunk discovered in the Forni Valley (adapted from Pelfini *et al.*, 2014).

The log was found at an altitude of 2,385 metres during work on a hiking trail. The log was buried about 4200-4030 years ago, during the period known as the Subboreal, a phase of climate transition after the Holocene Optimum. At the time, the tree was about 280 years old and therefore mature. The Forni glacier must have been much further upstream, and well-developed tree vegetation grew on the slopes of the valley, probably a high-altitude forest.

On the left side of the trail (ascending), hikers can observe rock plates smoothed by glacier erosion, displaying distinct brown, yellow, and reddish streaks caused by the oxidation of iron-bearing minerals within the metamorphic bedrock (fig. 9b). These rocks are particularly interesting for three main reasons. First, they are almost entirely devoid of vegetation or lichens, which makes it possible to appreciate the pristine geological surface recently uncovered by the retreating glacier. Second, their color and structure are striking: alternating reddish and white layers are often folded into complex shapes. These rocks consist mainly of mica schists and gneisses, interspersed with quartz- and feldspar-rich layers that appear lighter in color and are typically more deformed. The reddish hues result from the presence of minerals such as mica and chlorite, rich in iron (Fe) and magnesium (Mg). Their geological history is long and complex. Although the precise age of the original sediments is uncertain, the first phase of metamorphism and deformation likely occurred during the Palaeozoic, probably in the Devonian period (ca. 420-370 Ma), while a second phase is linked to the Alpine orogeny (ca. 110-60 Ma). More recent processes, associated with exhumation and surface exposure, have led to the development of fracture zones that now shape the morphology of the surrounding alpine peaks. A third remarkable feature is the presence of giant potholes (i.e. circular depressions carved by rock fragments trapped in the swirling motion of glacier meltwater or basal ice). When water or ice flow remains consistent and the abrasive debris persists inside the cavity, the erosion deepens these holes significantly, sometimes to depths of several meters.

After crossing the stream on a small bridge, the trail continues along a steep ascent, where hikers must take care (especially after rainfall) as the glacially polished rock slabs in this section can become slippery.

Once at the top of the slope, the trail descends sharply through smoothed rock surfaces and scattered debris, reaching the rock step visible from Stop 8, where the glacier terminus was located in 1995 (Stop 10) during its rapid retreat following the 1970-1985 advance.

From here, the route crosses a suspension bridge over a secondary branch of the glacial stream, which is often dry. A narrower path continues to the right, marked by stone cairns, and leads hikers across a wide, flat area now colonized by fast-growing pioneer herbaceous and shrubby vegetation and young small saplings (Stop 10a, fig. 9c).

This landscape (stretching in front of the Forni Glacier) is a vast proglacial plain, formed in recent decades as the glacier has retreated. Known as a sandur (from the Icelandic term for "outwash plain"), this environment develops where meltwater streams slow and deposit sediment such as sand, gravel, and pebbles. In addition to sedimentation from meltwater, gravitational processes like landslides and debris flows contribute to shaping the terrain (Kostaschuk, 2001). The result is a sediment-rich surface characterized by braided channels that shift and evolve over time (Benn and Evans, 2010). At the Forni Glacier, this young, dynamic landform has become increasingly visible over the past 20 years and now serves as a natural open-air laboratory, offering a unique setting to observe the ongoing interplay between ice, water, sediment, and biological successions and to reconstruct the glacier's recent history as well as the widening and evolution of proglacial areas (Franzetti *et al.*, 2020).

Continuing along the trail, hikers reach a large boulder marked in red by the Lombardy Glaciological Service, which indicates the position of the 2010 glacier front (Stop 11).

The trail continues to the sites where the glacier front was located in 2016 (Stop 12) and in 2023 (Stop 13). From Stop 13, visitors have a clear view of the current glacier tongue, now extensively covered by debris. On its hydrographic left side, the surface is marked by frequent collapses, while on the right, it features a median or floating moraine. Since 2010, this glacier tongue has been regularly monitored by the Glacio-Ecology research group of the University of Milan, and various scientific instruments are often visible on its surface (Stop 13a). These include tools for studying high-altitude ecosystems and glacier-environment interactions.

In this area, artefacts from the First World War (e.g. ammunition and barbed wire) are frequently found. Their re-emergence is directly linked to the intense melting of recent decades, and they contribute to the historical significance of this portion of the park (Stop 13b). Also visible from this point (Stop 13c) is the Automatic Weather Station (AWS), installed in 2005 by the University of Milan in collaboration with local and national institutions (e.g. Senese *et al.*, 2018).

From the terminus of the Forni Glacier (Stop 13), hikers can return to the Rifugio Forni along two main options: i) retrace the same path taken during the ascent, or ii) cross the second suspension bridge (locally known as the "Tibetan bridge"), which spans the glacial stream at the lower end of the sandur. Although this bridge is not used on the way up, it offers a scenic opportunity to observe the glacial torrent during peak melt conditions from above. After crossing, hikers may optionally continue to the Branca hut (2493 m a.s.l.) and descend back to the Forni hut via a different return route, completing the loop (fig. 9d).

### *The trail's dedication: Antonio Stoppani and Ardito Desio*

Antonio Stoppani (Lecco, 1824 - Milan, 1891) was a scientist, patriot, and one of the most prominent figures in the history of modern Italian geology. He held professorships at the University of Pavia and other major institutions and served as president of the Milan Section of the Italian Alpine Club. As director of the Museo Civico di Storia Naturale in Milan, he played a crucial role in promoting public understanding of the natural world. A prolific author, Stoppani contributed to the advancement of paleontology, volcanology, and Alpine geology. In his most well-known work, Il Bel Paese, he described the retreat of the "Forno Glacier" (as the Forni Glacier was called at the time), already noting changes in glacier dynamics that are now even more relevant. Stoppani remains a significant example of how scientific inquiry can foster public engagement with nature.

Ardito Desio (Palmanova, 1897 - Rome, 2001) was a geologist, explorer, and one of Italy's most internationally renowned scientific figures of the 20$^{th}$ century. After graduating in Natural Sciences from the University of Florence, he founded and directed the Institute of Geology at the University of Milan. His scientific curiosity led him to organize and lead numerous research expeditions to remote regions around the world, conducting fieldwork in geology, paleontology, and glaciology. Desio is best known for leading the successful 1954 Italian expedition to K2, the world's second-highest peak. A former president of the Comitato Glaciologico Italiano, he authored hundreds of scientific papers and volumes, and studied a lot of glaciers including the Forni Glacier extensively (documenting its variations since the 19$^{th}$ century). His legacy exemplifies how perseverance in scientific exploration can yield both knowledge and inspiration.

## DISCUSSION

### *Ephemeral infrastructures in fast-changing alpine environments*

Glaciological trails are inherently ephemeral: glacier retreat, permafrost degradation, and enhanced paraglacial activity can alter access, visibility of features, and safety within short intervals. Under such dynamics, trail planning should adopt flexibility as a design principle – minimizing new interventions, prioritizing pre-existing paths, and favoring modular signage and bridges that can be relocated or updated as conditions evolve. In the Forni Valley, replacing a flood-damaged bridge with a robust wooden structure (fig. 9d) that also hosts hydrological instrumentation exemplifies multi-functionality and low added impact.

To frame our approach within global practices, tab. 3 summarizes selected glaciological trails worldwide, chosen for their documented educational content and official web

Table 3 - List of other glaciological trails offered to tourists and trekkers in other countries. The main features are reported.

| Country | Trail Name | Educational Content | Multilingual Info | Website Available | URL | Notes |
|---|---|---|---|---|---|---|
| Switzerland | Morteratsch Glacier Trail | Panels, QR codes | Yes | Yes | https://www.maps.engadin.ch/it/tour/sentiero-tematico/sentiero-del-ghiacciaio-morteratsch/23436574/ | Accessible trail with historical glacier data |
| USA | Mendenhall Glacier Trail | No | No | Yes | https://www.fs.usda.gov/r10/tongass/recreation/trails/east-glacier-trail#:~:text=Directions,to%20the%20Nugget%20Creek%20Trail. | Focus on hiking, limited educational material |
| Canada | Athabasca Glacier Walk | Guided tours | No | Yes | https://www.banffjaspercollection.com/attractions/columbia-icefield-adventure/ | Part of Columbia Icefield experience |
| France | Glacier Blanc Trail | Panels | No | Yes | https://destination.ecrins-parc-national.fr/en/trek/903307-The-White-Glacier | Located in Parc des Écrins |
| New Zealand | Franz Josef Glacier Walk | Guided tours | Yes | Yes | https://www.franz-josef-glacier-tours.com/?ci=1&cm=21116992954__c_x-___&gad_source=1&gad_campaignid=22504380149&gbraid=0AAAAACRC-4b15qKl_2NZ2AOGh-wWGPHUrJM&gclid=EAIaIQobChMI7LG_oYL6jwMVXq-DBx-1ZIRlDEAAYASAAEgLiTvD_BwE | Includes safety and climate info |
| Nepal | Sagarmatha National Park Trails | Panels, local guides | No | Yes | unesco.org https://www.nepalhikingteam.com/sagarmatha-national-park | Includes FOREST-GLOF project areas |
| Italy | Stoppani-Desio Trail | Panels, QR codes, videos | Yes | Yes | sites.unimi.it/glacio/sentierostoppanidesio.it | Multilingual, inclusive, replicable model |

presence. Most initiatives emphasize scenic and recreational aspects, with limited integration of scientific outreach or dynamic content updates. Only a few trails (e.g., Morteratsch in Switzerland, Franz Josef in New Zealand) provide multilingual information or combine interpretive panels with digital resources. None of the surveyed examples report visitor statistics or include real-time scientific data. Against this backdrop, the Stoppani-Desio Trail introduces several distinctive features: (i) modular signage linked to a centralized digital platform for rapid updates; (ii) multilingual content (Italian, English, German) tailored to the linguistic context of Stelvio National Park; and (iii) integration with ongoing scientific monitoring (hydrological stations, AWS, UAV surveys), positioning the trail as a dynamic open-air laboratory. These elements enhance replicability and resilience under conditions of rapid environmental change, offering a scalable model for future initiatives.

*Positioning within Alpine and international practice*

A concise literature overview highlights complementary approaches across the Alps and worldwide. The Morteratsch Glacier Trail documents retreat and accessibility changes through curated wayfinding and interpretive media (Maisch *et al.*, 1993). At the Alpine scale, glaciological interpretation and geotourism resources -field trips, virtual tours, and panel-equipped itineraries-demonstrate multiple modalities to reach non-specialist audiences (Cayla, 2009; Perotti *et al.*, 2020; Salim *et al.*, 2021). Against this backdrop, the Stoppani-Desio Trail's distinctive contribution lies in combining physical signage with multilingual, centrally updated digital content, allowing rapid integration of new data, hazard notices, and route adjustments. This approach is consistent with other innovative educational tools, such as the VR Glaciers and Glaciated Landscapes project (McDougall, 2019), which offers immersive virtual field experiences for glaciology students and the general public, including a trail along the Roseg Glacier (https://vrglaciers.wp.worc.ac.uk/Roseg2008/).

Ultimately, the trail functions not merely as a route through space, but as a pathway through knowledge: a medium to interpret glacial landscapes and to convey the urgency of climate change in a direct, immersive, and transformative way. This comparative overview provides the basis for the following discussion on inclusive communication and digital adaptability, highlighting how the Stoppani-Desio model advances beyond conventional practices.

*Inclusive communication and digital adaptability*

Static panels alone struggle to keep pace with moving termini and evolving proglacial landscapes. Hybrid strategies – short, site-specific texts; QR-based access to multimedia; and centralized web management – offer adaptable communication that supports safety, orientation, and scientific outreach. This also facilitates accessibility (e.g., language, format), broadening engagement with diverse user profiles. Digital platforms should remain light, validated, and updateable, prioritizing clarity over volume to avoid information overload.

*Shared governance and maintenance*

Long-term resilience depends on shared governance involving protected area managers, local authorities, academic partners, and mountain professionals (guides, leaders, rangers). Distributed responsibilities can accelerate maintenance, ensure coherent messaging, and support risk monitoring and visitor education. For Stoppani-Desio, a dual arrangement – park authority for physical infrastructure and university partners for digital curation – has proven effective for timely updates and consistent scientific framing.

*Replicability and impact evaluation*

Core principles are transferable to other glacierized regions: adaptive routing, minimal-impact infrastructure, multilingual digital content, and collaborative governance. Replication should build on existing paths and facilities, engage stakeholders early, and include a simple evaluation framework (e.g., user feedback, safety incidents, content access metrics).

A comparative framework across Alpine and other mountain regions could be instrumental in assessing the effectiveness, resilience, and public impact of glaciological trails. Shared performance indicators (e.g. visitor numbers, user satisfaction, scientific outreach, and educational impact) should be defined and monitored over time. In this context, the integration of visitor feedback tools, periodic environmental assessments, and maintenance protocols is essential to ensure that each trail remains safe, informative, and responsive to ongoing landscape changes.

Beyond knowledge transfer, glaciological trails aim to foster responsible behaviors by coupling emotional engagement with clear, evidence-based interpretation of climate-change effects on ice, water, sediment, and biota.

Overall, the Stoppani-Desio Trail demonstrates that concise, modular interpretation – tied to real-time scientific observation – can sustain educational value as landscapes change. By treating trails as dynamic interfaces between visitors and alpine processes, we can support safe access, public understanding, and stewardship of rapidly transforming cryospheric environments.

## CONCLUSIONS

Climate change is profoundly reshaping glaciated mountain environments, calling for innovative strategies in education, outreach, and sustainable tourism. The design and implementation of the Stoppani-Desio Glaciological Trail offers a concrete and forward-looking response to these challenges, by integrating scientific research, inclusive planning, and multilingual communication tools.

Several glaciological trails worldwide (e.g. the Morteratsch Glacier Trail in Switzerland, the Franz Josef Glacier Walk in New Zealand, and the Sagarmatha National Park routes in Nepal) provide valuable educational experiences. However, only a few combine on-site infrastructure (e.g., interpretive panels, QR codes, thematic maps) with dynamic digital content and multilingual accessibility. Most focus primarily on scenic or recreational aspects, with limited integration of scientific outreach.

The Stoppani-Desio Trail stands out for its i) 13 thematic observation points linked to historical glacier positions and scientific topics, ii) multilingual QR codes (i.e., Italian, English, German) connecting users to a centralized, updateable digital platform, iii) inclusive and adaptive design, accessible to a wide range of users in a rapidly changing landscape, and iv) integration with scientific monitoring instruments (e.g., meteorological and hydrological stations).

This trail functions as a dynamic open-air laboratory where landscape interpretation, hazard awareness, and scientific literacy converge. Its participatory design (uniting researchers, local authorities, park managers, volunteers, and mountain professionals) shows how interdisciplinary collaboration can support resilient, low-impact infrastructure in sensitive alpine settings.

This case study offers a replicable model for glaciological trails in other mountain regions affected by climate change. The modular trail structure, multilingual communication tools, and hybrid digital-physical format provide a flexible and scalable framework for mountain-based climate education.

Crucially, the trail is managed through a dual-governance model: the Stelvio National Park is responsible for physical infrastructure and safety, while the University of Milan curates and updates the online content in real-time, including emergency communications when needed. This arrangement ensures rapid adaptation to landscape changes and effective dissemination of scientific information.

Glaciological trails, when thoughtfully designed, are not just routes across a landscape: they are pathways to knowledge, memory, and action. By fostering emotional and cognitive connections with rapidly vanishing glaciers, they promote environmental awareness and may inspire more responsible behavior in the face of the climate crisis.

## AUTHOR CONTRIBUTION

All authors conceived and planned the project. C.S., A.S., M.D., M.P., M.Z. and G.A.D. wrote the manuscript with input from all authors. A.S., R.A., S.M. and G.A.D discussed the results and commented on the manuscript.

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