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Phytosociology of the vegetation communities of the Stelvio Pass area

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ABSTRACT

High elevation areas are sensitive and vulnerable to climate change and exhibited relatively rapid changes in response to warming involving changes of floristic composition, species upward migration, shrub and tree encroachment and surface area changes. For this reason, it is important to provide quantitative studies as tools allowing a long-term monitoring of vegetation in response to climate change. The Stelvio Pass area is a high elevation site located in the European Alps, and a unique case study on the alpine range providing historical detailed information on vegetation with the availability of phytosociological maps of vegetation elaborated in 1953 and 2003. Here we show and describe an updated and detailed phytosociological vegetation mapping which will constitute a robust base for the monitoring and quantitative assessment of any impacts of future climate and/or environmental change as well as a tool to plan suitable vegetation and biodiversity conservation actions in the alpine environment.

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European Alps; vegetation mapping; phytosociological relevés; vegetation monitoring

1. Introduction

High elevation areas are among the most sensitive and vulnerable environments to climate change with relevant impacts both on their biotic (e.g. vegetation) and abiotic (e.g. glaciers, permafrost) components (e.g. IPCC, 2014). Among high elevation areas, the European Alps have been experiencing the strongest atmospheric warming, especially in the period 1950–2000 (Auer et al., 2007; Gobiet et al., 2014), with consequences on abiotic and biotic compartments of the ecosystems (Beniston et al., 2018; Cannone et al., 2007; Cannone et al., 2009; Cannone & Pignatti, 2014; Elmendorf et al., 2012; Gottfried et al., 2012; Lenoir et al., 2008; Steinbauer et al., 2018).

Evidences of climate change impacts on the alpine vegetation involve plant phenology (Rogora et al., 2018; Theurillat & Guisan, 2001), changes in community composition, extinction debt and thermophilization (e.g. Cannone et al., 2007; Cannone & Pignatti, 2014; Gottfried et al., 2012; Keller et al., 2005), upward migration of alpine species on mountain summits (Lenoir et al., 2008; Pauli et al., 2012; Steinbauer et al., 2018), shrub and tree encroachment (Cannone et al., 2007; Leonelli et al., 2016; Malfasi & Cannone, 2020) surface area changes (Cannone et al., 2007). Moreover, a dramatic reduction of suitable habitats for alpine plants is predicted by the end of the twenty-first century (Dirnböck et al., 2011; Engler et al., 2011). Beyond climate, land use change could be another important driver of vegetation change (Komac et al., 2011; Mayer & Erschbamer, 2017). For this study area, it was assessed that shrub encroachment was related to climate change and not to land-use change by analysing the specific relation between shrub recruitment, climatic data and grazing data, indicating that shrub encroachment started in the late 1860s, at the end of the Little Ice Age (Malfasi & Cannone, 2020). In the last decades also tree encroachment was observed in this area and it was assessed that it was promoted by the increase and persistence of warming with only a weak relation with grazing (Malfasi & Cannone, 2020).

Most studies on climate change impacts on the alpine tundra vegetation relied on three main approaches: manipulative experiments, historical comparisons (permanent plots and quasi-permanent plots) and space-for-time substitutions along environmental gradients (Kapfer et al., 2017). These are all valuable strategies allowing to assess both past and future vegetation changes (Chytrý et al., 2014). However, precise vegetation surveys and floristic information over time are the basis to monitor and quantify the impacts of climate change and to support future management and conservation plans (i.e. Stoll et al., 2015). While networks of permanent-plots and historical mountain summits with floristic information are relatively well represented (Gottfried et al., 2012; Rogora et al., 2018; Steinbauer et al.,

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2018), detailed and historical data of plant communities distribution (vegetation and phytosociological maps) in mountain areas are scarce, available only from the lower elevation belts (e.g. Garbarino et al., 2014; Velli et al., 2019) or with a coarse spatial resolution (e.g. Mietkiewicz et al., 2017).

In this frame, a unique case study on the alpine range is represented by the Stelvio Pass, a high elevation site (2230–3095 m asl) in the Italian central Alps. Here a detailed phytosociological map of vegetation communities completed by phytosociological relevés was produced in 1953 at scale 1:12,500 (Giacomini & Pignatti, 1955). Fifty years after (in 2003) the vegetation was re-sampled showing shrub encroachment and changes in plant community and species composition in response to recent climate change impacts (Cannone et al., 2007; Cannone & Pignatti, 2014).

Here during the summer 2018, we produced a new phytosociological vegetation map of the Stelvio Pass area (Italian central Alps) at scale 1:2000 (main map). Our aim is to provide a detailed base for the monitoring and quantitative assessment of any impacts of future climate change as well as a tool to plan suitable vegetation and biodiversity conservation actions in the alpine environment.

2. Study area

The study area is located in the Stelvio National Park (Italian central Alps), close to the Stelvio Pass (46°31′ N, 10°25′ E; elevation 2230–3095 m asl; Figure 1), and includes the subalpine (2200–2400 m asl), alpine (2400–2800 m asl) and nival belts (>2800 m asl). Within the study area, a surface of 583.4 ha was surveyed, of which 1.91 ha (0.33%) was excluded from the further cartographic elaboration because of the occurrence of actual anthropogenic disturbance (football field and nordic sky trail). The extent of the map is given by 46°30′58.2″N, 10°24′30.6″ E (lower left corner) and 46°32′24.3″N, 10°27′72.0″E (upper right corner) and represents an extent already investigated also by both Giacomini and Pignatti (1955) and by Cannone et al. (2007).

Climatic data (period 1978–2018) from the nearest available meteorological station at Cancano (46° 31′02.2″N, 10°19′14.7″E, 1948 m asl, 9 km to E–SE) indicate a mean annual air temperature of + 3.3 ± 0.8°C. Mean annual precipitation sum is 817 mm.

The bedrock is mainly siliceous (consisting of granitic and granodioritic ortogneiss and of biotic or two micas paragneiss), with some localized outcrops of calcareous rock in the south-west sector of the

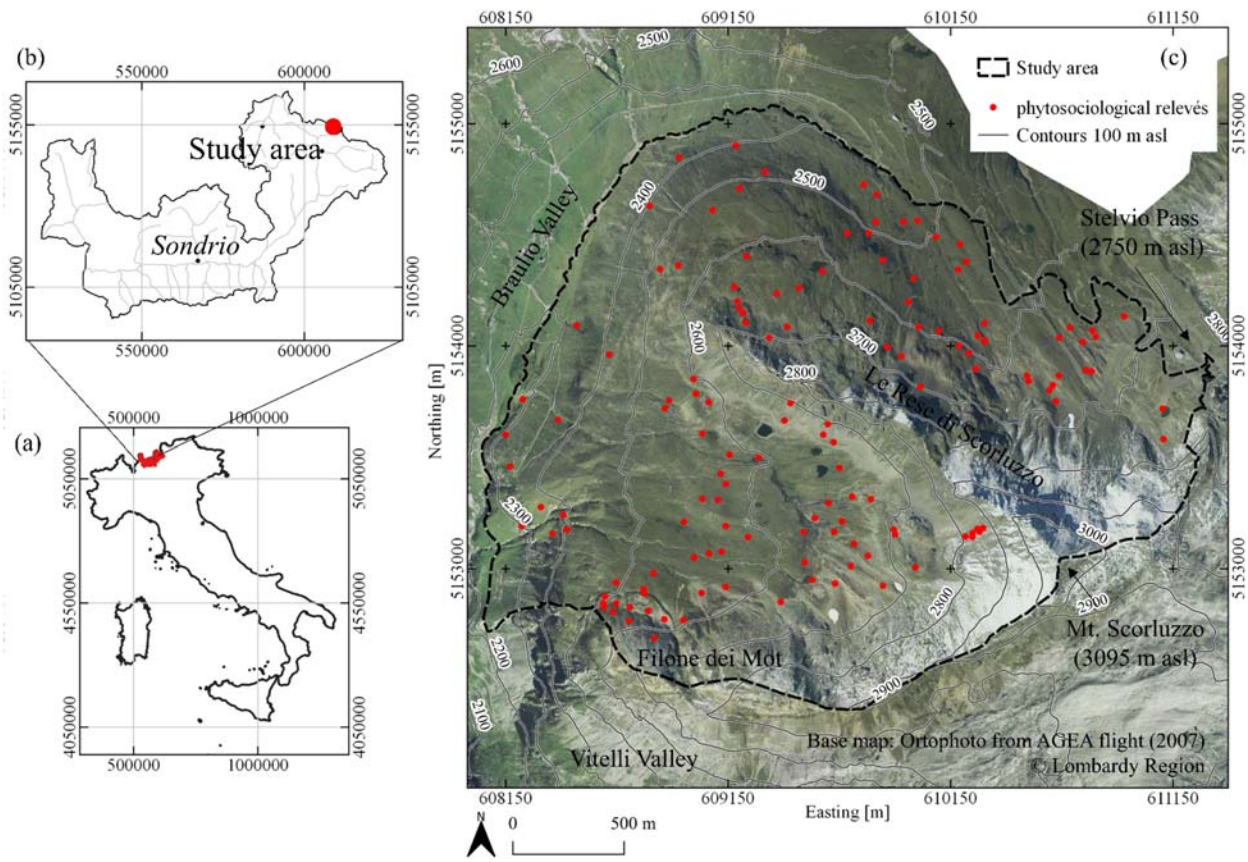

Figure 1. Study area with reference to (a) the site location within Italy, (b) within Sondrio Province, and (c) the specific location in the Stelvio Pass area. Base map: Ortophoto from AGEA flight (2007), pixel size 0.5 × 0.5 m. © Lombardy Region. Projected coordinate system WGS84_UTM32N (EPSG 32632).

study area (Guglielmin & Tellini, 1992; Montrasio et al., 1990).

Permafrost is sporadic at elevations between 2400 and 2700 m (Cannone et al., 2003), and discontinuous above (Guglielmin & Siletto, 2000). Nevertheless, 1 km east from the study area at 3000 m, the permafrost thickness exceeds 200 m (Guglielmin et al., 2018). The Little Ice Age (LIA) started AD 1560 and ended in AD 1860 (Guglielmin et al., 2018), whereas the maximum extension of the glaciers during the Holocene reaching 2610 m asl (Cannone et al., 2003).

Vegetation is a mosaic of habitat types including chionophylous alpine shrubs, alpine dwarf shrubs of the wind-swept areas, alpine grasslands, snowbeds, wetlands, pioneer vegetation and barren ground. The tree species line (Körner & Paulsen, 2004) in this area is formed mainly by seedlings and saplings of *Larix decidua* Mill. and *Pinus mugo* Turra, with few individuals of *Picea abies* var. *abies* (Malfasi & Cannone, 2020).

3. Materials and methods

3.1. Data sources

The data used to develop the detailed map of vegetation distribution at the Stelvio Pass area (Italian central Alps), were achieved based on the fieldwork carried out during the summer 2018. For this purpose, prior to the field activity we collected the information available from Giacomini and Pignatti (1955) (Figure S1) and from Cannone et al. (2007), who mapped and characterized the plant communities distribution in 1953 and 2003 respectively, to achieve comparable data. The first phytosociological map of the Stelvio Pass area at scale 1:5000 covered an extent given by 46°29′59.8″N, 10°23′0.43″E (lower left corner) and 46°33′01.2″N, 10°27′23.3″E (upper right corner). It was performed in 1953 and it represented the first example of similar investigations on the alpine vegetation in the mountain regions of Italy.

The historical map was georeferenced aligning 4 control points that were identifiable on the recent digital topographic map (Regional Technical Map 1:10,000), with a root mean square (RMS) error of less than 1 m in X and Y directions. In 2003 a second survey of the vegetation was performed at scale 1:2500 and georeferenced following the same criteria, allowing the first assessment of the vegetation changes over 50 years (Cannone et al., 2007).

The syntaxonomic organization and the diagnostic species of plant communities of subalpine and alpine belts were identified following: Giacomini and Pignatti (1955), Giacomini (1960), Credaro and Pirola (1975), Biondi et al. (2014) and Leuschner and Ellenberg (2017) (Table 1 Supplementary Materials) and are coherent with the syntaxonomical framework of the Prodromo della vegetazione d'Italia (http://www.prodromo-vegetazione-italia.org/).

The field survey for the elaboration of the new phytosociological map was performed during the summer 2018. The overlay of the Regional Technical Map (sheets D1d3, D1d4) and of the last phytosociological map (Cannone et al., 2007) was used as a printed base map for the field activity and as a helpful tool to detect the current distribution of the plant communities, that was performed at 1:2000 scale in agreement with the previous data. Five A1 sheets (841 × 594 mm) were necessary to cover the whole study area. The same base map was also uploaded as a custom file (file format .kmz) in the GPS device used on the field (Garmin eTrex 30; accuracy ± 3 m), to retrieve better information on the position during the survey. In addition, georeferenced ortophoto and Digital Terrain Model (DTM, cell size 5 × 5 m) were used in the vectorization process and in the further spatial analysis within different altitudinal ranges. Data sources are summarized in Table 1.

3.2. Field data

The field activity was carried out from mid-July to late-August 2018. Using the printed topographic

Table 1. Data used for the field activity and the data elaboration. CTR and Ortophoto served as base map for the vegetation resurvey in 2018, while the vegetation map 2003 (Cannone et al., 2007) provided the most recent distribution of the plant communities in the study area. DTM 5X5 was used to extract contour lines and zonal statistics.

Name	Format	Temporal coverage	Description	Source
Vegetation map 1953	Vector (polygon)	1953	First assessment of the plant community of the Stelvio Pass area. (obtained from head-up digitalization of a scanned copy of the original map)	Giacomini and Pignatti (1955)
Vegetation map 2003	Vector (polygon)	2003	First re-survey of the plant communiies of the study area since 1953	Cannone et al. (2007)
CTR	Raster (Tagged Image File Format, TIFF)	2012	Regional Technical Map (sheets D1d3, D1d4), scale 1:10,000	Lombardia Region[a]
DTM 5X5	Raster (Digital Terrain Model, DTM)	2015	Digital terrain model of 5 × 5 m cell size of Sondrio province, further clipped over the study area	Lombardia Region[a]
Ortophoto	Raster (Tagged Image File Format, TIFF), Web Map Service (WMS)	2018	Ortophoto from AGEA flight, pixel size 0.5 × 0.5 m	Lombardia Region[a]

[a]Lombardia Region Geoportal: http://www.geoportale.regione.lombardia.it/ All the data were analysed with the projected coordinate system WGS84_UTM32N (EPSG 32632).

base map at scale 1:2000 and the GPS, stream and lakes, rock outcrops, bare ground (areas with no vegetation coverage) and vegetation (areas with vegetation coverage > 1%) were mapped, recording the location, boundaries and shape of each feature. For vegetation mapping, each patch of plant communities was reported on the map and for each mapped patch was carried out a phytosociological relevé, randomly placed on homogeneous vegetation within each investigated patch, according to the protocol already adopted by Cannone et al. (2007). The IDs of each feature (vegetated and not vegetated) were written on the printed base map (attribute name: ID) and corresponding information in the field data book. The phytosociological survey was performed to achieve a detailed description and characterization of the vegetation communities. For this aim, the phytosociological relevés were carried out in the same site and using the same criteria already adopted by Cannone for the survey performed in the summer 2003 (Cannone et al., 2007; Cannone & Pignatti, 2014). In particular, during the survey 2018 were performed 145 phytosociological relevés with a fixed size of 16 m^2, fully comparable with 145 of the 159 relevés performed in 2003 (Cannone et al., 2007; Cannone & Pignatti, 2014) and with 50 of the 171 relevés performed in 1953 (Giacomini & Pignatti, 1955). GPS location (accuracy ±3 m) and photos from different point of views allow to enable reliable future resurvey. For each relevés were recorded total vegetation % cover, the species list and % coverage of each plant species (visually estimated with a range from 0% to 100%, allowing not to lose information on lower coverage values) (Cannone et al., 2007; Cannone & Seppelt, 2008; Favero-Longo et al., 2012), Each vegetation patch was identified and described on the basis of (a) coverage, (b) physiognomy and (c) phytosociological relevés (Cannone et al., 2007; Cannone & Seppelt, 2008; Favero-Longo et al., 2012), focusing on the occurrence and on coverage of characteristic and diagnostic species of the subalpine and alpine plant communities.

The field data were used to cluster the vegetated areas in homogeneous groups and for further statistical analyses to identify the vegetation communities. In the field were observed also mosaics of different vegetation communities: in this case the phytosociological survey was performed separately for each vegetation community in order to describe them in detail. In addition, three types of surfaces devoided by vegetation were identified and mapped: bare ground, rocks, alpine lakes and streams.

Vascular plants were identified up to the species level, whereas cryptogams were grouped as mosses and lichens. Species determination and nomenclature was standardized following Pignatti (1982), Lauber and Wagner (1998), Conti et al. (2005), and Wilhalm et al. (2006).

3.3. Vegetation classification system

In 1953 Giacomini and Pignatti (1955) described and classified the vegetation of the Stelvio Pass area, publishing the first phytosociological map and describing the species composition, frequency and coverage at different syntaxonomic levels (Classes, Orders, Alliances, Associations).

Vegetation data collected from the phytosociological relevés in 2018 were analysed by means of hierarchical classification providing a tree clustering (dendrogram) applying the Ward's method for the linkage and the squared Euclidean distances through the software STATSOFT®. The dendrogram identified groups of relevés in agreement with the syntaxa identified by Giacomini and Pignatti (1955), Giacomini (1960), Credaro and Pirola (1975), Leuschner and Ellenberg (2017) and the syntaxonomical framework of the Prodromo della vegetazione d'Italia (http://www.prodromo-vegetazione-italia.org/). The results of the hierarchical classification allowing to finalize the phytosociological map based on the field data surveyed in 2018.

3.4. Method of vectorization and data analysis

The field map drawn in summer 2018 was scanned, geo-referenced on the Regional Technical Map (with a RMS error less than 1 m, in agreement with the previous maps) and visually digitalized to obtain a single vector layer (ESRI shapefile format) composed of 1076 polygons. The vegetation associations were merged in a single attribute table based on the identification code of each polygon.

Contour lines of 100 m interval (2400, 2500, 2600, 2700, 2800, 2900, 3000 m asl) were extracted from the DTM 5×5 m and used to clip the study areas in altitudinal ranges. Areal extension of vegetation associations was computed for each altitudinal ranges and for the whole study area.

Data were georeferenced, digitalized and analysed with the open-source program QGIS (3.4.11; QGIS Development Team, 2009). Original layers (in vector and raster formats) and field map were all georeferenced to the projected coordinate system WGS84_UTM32N (EPSG 32632). Multivariate statistics of phytosociological data were analysed using STATSOFT®. Graphs were produced with Microsoft Excel (2016) and STATSOFT®.

4. Results and discussion

The area mapped during summer 2018 occupied 581.5 ha and was located between 2230 and 3095 m, with

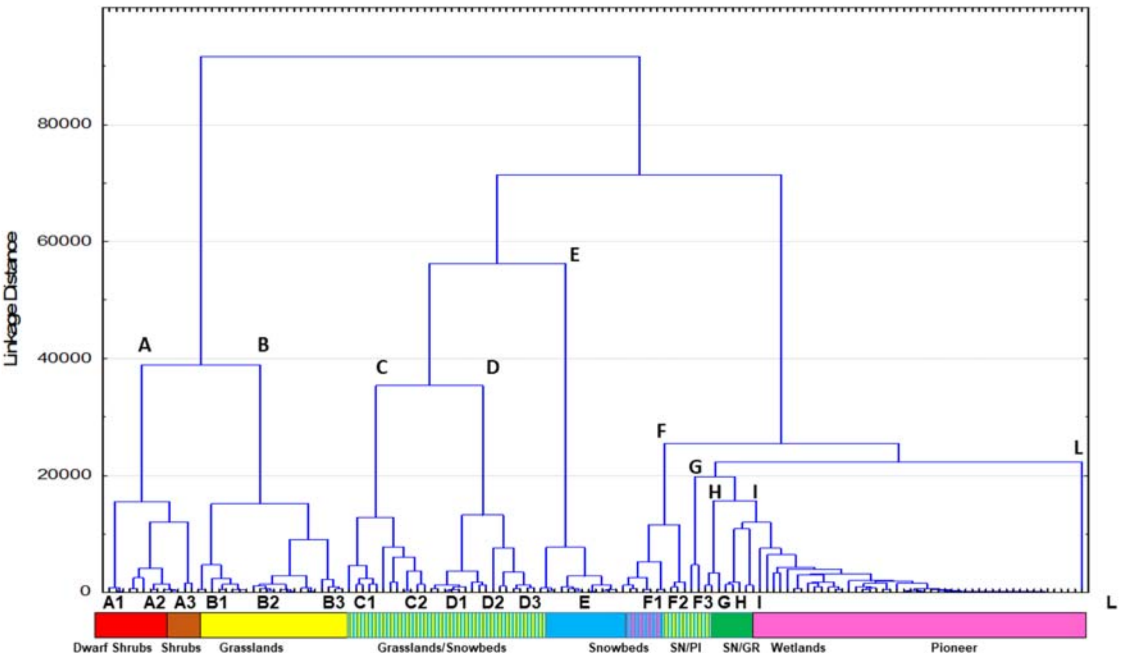

Figure 2. Dendrogram showing the hierarchical classification of the 145 phytosociological relevés. Legend: see Tables S1 and S2 for abbreviations and the colours representing the ecological series. Legend: SN/PI = mosaic snowbed and pioneer; SN/GR = mosaic snowbed and grassland.

more than 60% of the surfaces located between 2500 and 2800 m.

The dendrogram provided by the hierarchical classification identified 10 main groups of relevés (A to L) (Figure 2, Table S1), including 46 vegetation communities, corresponding to 24 phytosociological associations and 22 mosaics of two different vegetation communities (e.g. *Luzuletum spadiceae/Salicetum herbaceae*), allowing to finalize the phytosociological map. Bare ground (BG), rock outcrops (Rock), streams and lakes (water) were also reported, for 49 total classes represented in the phytosociological map. The phytosociological survey allowed to emphasize the characteristics of the vegetation communities occurring in the study area (Figures 2 and 3, Table S1). Group A referred to the alpine dwarf shrubs (A1, *Loiseleurieto-Cetrarietum* in transition with the alpine grassland *Caricetum curvulae*, and A2 *Loiseleurieto-Cetrarietum* in pure stands), where wind action decreases the winter snow cover, and to alpine shrubs (A3, *Vaccinium-Rhododendretum*) communities, associated to thicker snow cover protecting them from the freezing damage (Cannone & Pignatti, 2014; Credaro & Pirola, 1975; Giacomini & Pignatti, 1955; Leuschner & Ellenberg, 2017). Groups B and C identified the alpine grasslands both typical (*Caricetum curvulae*, group B) as well as in transition towards snowbeds where snow cover melts later (*Hygrocurvuletum*, group C). Groups D, E and F identified the snowbeds communities (*Salicetum herbaceae*), separating those dominated by *Alchemilla pentaphyllea* (Group D, *Salicetum alchemilletosum*) and indicating an earlier snowmelts as well as a later successional stage, than the typical *Salicetum herbaceae* dominated by *Salix herbacea* (Group E, *Salicetum salicetosum)*, to its transition towards the pioneer community *Luzuletum spadiceae* (Group F) (Cannone & Pignatti, 2014; Credaro & Pirola, 1975; Giacomini & Pignatti, 1955; Leuschner & Ellenberg, 2017). Groups G and H represent wetlands, with the identification of *Caricetum fuscae* (Group G) and of its transition to the *Eriophoretum scheuchzeri* (Group H). Group I is very large and includes different pioneer and early-successional communities (*Androsacetum alpinae*, *Oxyrietum digynae*, *Luzuletum spadiceae*), indicating the occurrence of both pioneer and early –successional communities, as well as some isolated relevés representing snowbeds on calcareous rocks (*Salicetum retusae-reticulatae*), calcareous grasslands (*Caricetum firmae; Elynetum*) and dwarf shrubs (*Dryadetum*). Group L, represented by only one relevés, identified an initial *Caricetum curvulae* dominated by *Anthoxanthum alpinum*.

The phytosociological map (Figure 3) showed that the study area was characterized by a heterogeneous vegetation, with a large number of communities and their mosaics. Overall, 26 associations reported in literature were detected, of which 6 were found as pure stands only (ODc, SHs, SSR, CCc, SS, DP), 2 as mosaics with other associations only (AN, NA) and 18 both as pure stands as well as mosaics (AA, OD, LS, SH, SHa, CFu, ES, CC, CCi, HA, CN, FH, DO, CFi, EM, LC, LCc, VR) (Table S2).

The phytosociological map showed that 12 vegetated classes accounted for more than 60% of the surface of the study area (Table S3) (HC: 12.0%; CC: 10.1%; LC: 7.6%; OD: 7.5%; CCc: 6.0%; LS: 5.3%;

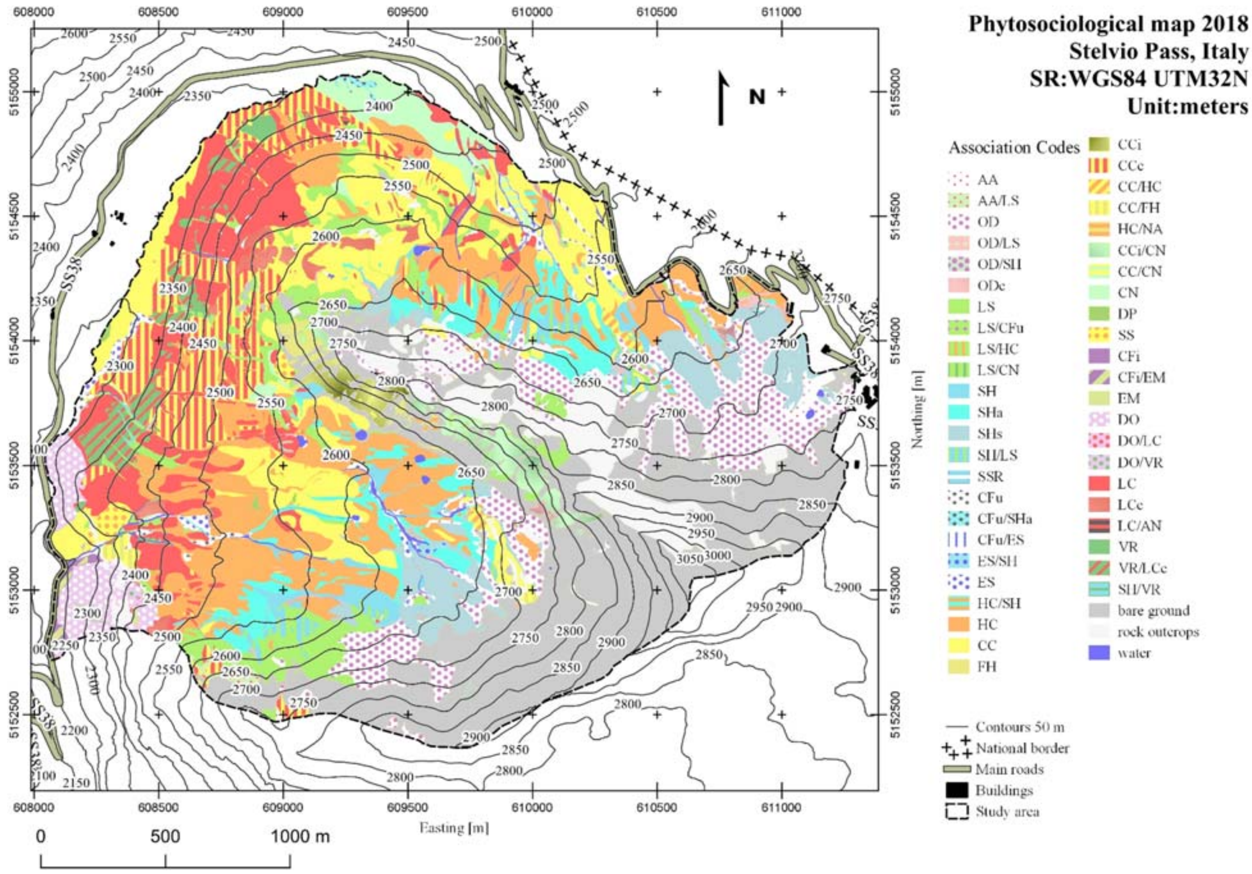

Figure 3. Phytosociological map of the vegetation of the study area, obtained following the vegetation classification according to the hierarchical classification and multivariate analysis.

SHs: 4.0%; SHa: 3.6%; DO: 2.0%; CN: 1.8%; VR/LCc: 1.6%), while each of the remaining phytosociological classes covered less than the 1.5% of total area.

The highest variability in phytosociological classes was reported between 2400-2500 m, as indicated by the highest number of classes (34) compared to the relative small extent of the altitudinal range (12.2% of the investigated area). The larger available surface at 2500–2600 m (21.7%) and 2600–2700 m (26.0%) was characterized by a large number of classes (32 and 32, respectively), whereas since 2700 m upward the variability decreased in agreement with the total surface reduction. Among the observed vegetation communities, the alpine grasslands were the most widespread and well represented in all altitudinal ranges up to 2700 m asl, showing the maximal frequency between 2500 and 2600 m. They were mainly characterized by the climax community of the alpine grasslands (*Hygrocurvuletum* and *Caricetum curvulae*), that together accounted for the 78.5% of all grasslands. Communities representing the initial development of *Caricetum curvulae* or its transition to other grasslands (CCi/CN) were able to reach elevation above 2800 m, colonizing stable south-exposed slope characterized by early snowmelt. Between 2230 and 2600 m, on gentle and North-exposed sites occasionally grazed, were frequently found also patches of *Carici curvulae-Nardetum* (CN), where the highly generalist species *Nardus stricta* established and co-dominated within the *Curvuletum*. Interestingly, the new association of tall-herbs *Deschampsio caespitosae-Poetum alpinae* (DP) was found in three small and localized sites on gentle slopes, where soil enrichment due to cattle herd occurred.

Pioneer communities were the second most abundant communities of the study area, especially at 2600–2700 m, mainly represented by *Oxyrietum digynae* (OD) that colonized the scree slopes and debris covered surfaces. Also the early-successional *Luzuletum spadiceae* (LS) reached its optimum between 2600 and 2700 m, but it was also found at lower altitudinal ranges where it colonized areas with exposed soil and surface instability and likely snow cover accumulation. At 2500–2700 m, in South-West to South exposed sites, with good nutrient and water supplies, was also reported a pioneer community characterized by the occurrence of *Cirsium spinosissimum* (ODc).

At the lower altitudinal ranges (from 2230 to 2500 m), the alpine dwarf shrubs were the more abundant plant communities, forming pure stands (*Loiseleurieto-Cetratietum*, LC; *Loiseleurieto-Cetratietum* Br-Bl 1926 *cladinetosum*, LCc) or mosaics with the alpine grassland (CCc), as well as the alpine shrub community characterized by the occurrence of *Rhododendron* *ferrugineum* encroached by trees (*Pinus mugo* and *Larix decidua*) (*Vaccinium-rhododendretum ferruginei extrasylvaticum,* VR), which made their ingression since the 1970s in response to climate warming persistence (Malfasi & Cannone, 2020).

Snowbed communities were the fourth more common vegetation of the study area, involving both the *Salicetum herbaceae alchemilletosum* (SHa), as well as the typical *Salicetum herbaceae* (SHs). These communities mainly occurred as pure stands with a core distribution between 2500 and 2800 m, even if small mosaics with alpine shrubs and wetlands occurred also in the lower altitudinal ranges. The distribution patterns of the different types of *Salicetum herbaceae* allow identify areas with different snow cover persistence and a trend to evolve towards grasslands (in particular where *Alchemilla pentaphyllea* becomes dominant).

Finally, the wetlands were the less abundant communities and were located to marsh and spring areas or to edges of water bodies from 2230 to 2600–2700 m.

Comparing the present map with the historical map produced by Giacomini and Pignatti (1955) we can confirm the trends already outlined by Cannone et al. (2007) of shrub encroachment, further followed by tree encroachment in the last decades (Malfasi & Cannone, 2020), as well as the regression of the alpine grassland and the general upward displacement trend of most vegetation communities.

5. Conclusions

In this paper, we characterized and described the composition and the spatial distribution of plant communities of the Stelvio Pass area, 65 years after the first survey (1953). The phytosociological map shows the actual development of vegetation across the study area providing a robust baseline for future monitoring and quantitative assessment of any impacts of future climate and/or environmental change, as well as a tool to plan suitable vegetation and biodiversity conservation actions in the alpine environment.

Software

All stages of the map production, which included georeferencing, digitizing, DTM analyses, data collection and final layout, were carried out using the open-source program QGIS (3.4.11; QGIS Development Team, 2009).

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We thank Stelvio National Park for logistical support. NC conceived the study; FM and NC performed the field survey; NC made the statistical analyses; FM elaborated the maps; NC and FM participated in writing the paper.

Data availability statement

Authors agree to make data and materials supporting the results or analyses presented in their paper available upon reasonable request. The dataset developed in this research includes a single ESRI polygon shape file (ESRI Inc., http://esri.com) composed by a polygon identification number (ID; integer) and plant association classes (ASS; string). The definition and the syntaxonomic organization of each class is given in Table S2.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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