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Extending the interpretation of Natura 2000 habitat types beyond their definition can bias their conservation status assessment: An example with species-rich *Nardus* grasslands (6230*)

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ABSTRACT

In this study, taking as an example the species-rich *Nardus stricta* grasslands (habitat 6230*) within the Natura 2000 network of the Lombardy region (northern Italy, central southern Alps), we evaluated i) whether the spatial distribution of the habitat 6230* corresponded to essential features for its identification, and ii) whether a broad habitat interpretation could affect its regional conservation status assessment.

We analysed the spatial distribution of habitat 6230* regarding the elevation, geological substrate, forest treeline, land use types and other habitat types. Using the regional database of habitat relevés, we calculated the threshold values of conservation status for a range of indicators of structure, functions and future prospects. To this end, we used a subset of relevés of the subalpine sub-type of habitat 6230*, as it corresponds to plant communities where habitat interpretation can easily be extended beyond its definition.

The mapped distribution of habitat 6230* did not entirely match the essential features required for its identification. Some polygons were located at the ecological extremes of habitat 6230*, on carbonate substrates and in the alpine belt. In those conditions, the habitat showed an Unfavourable-bad (U2) conservation status, decreasing species richness and typical species dominance and frequency. Our findings highlighted that plant communities representing ecological extremes of the habitat type 6230* should no longer be referred to the same habitat type.

The proposed indicators can help identify habitat sub-types more conducive to successful restoration measures, thereby ensuring favourable conservation status. In turn, this guarantees sustainable agricultural land use, which simultaneously promotes biodiversity and high-quality food products. Furthermore, the procedure could be extended to other habitat types for early identification of priority monitoring areas, especially when their interpretation has gone beyond their definition, with little consideration given to the consequences on the regional conservation status assessments.

1. Introduction

The European Union's Habitats Directive (EU's HD; 92/43/EEC) defines natural habitats as terrestrial or aquatic, natural or semi-natural, areas that possess unique geographic, abiotic, and biotic features. Among them, natural habitat types of EU Community interest (hereafter "habitat") are included in the HD Annex I when they: i) are in danger of disappearance in their natural range, ii) have a small natural range following their regression or because of their intrinsically restricted area, ii) present outstanding examples of typical characteristics of one or more EU biogeographic regions. The HD requires the designation of Special Areas of Conservation (SACs) to protect and manage Annex I habitats and species of EU Community interest listed in the HD Annex II. The EU network of SACs, together with Special Protection Areas (SPAs), designed under the Birds Directive (79/409/EEC), is called the Natura 2000 (N2K) network.

After the implementation of the HD, habitats interpretation has received legislative significance (Rodwell et al., 2018). Substantial efforts have been made to clarify habitats interpretation (EC, 2013), even at the national (see Evans, 2010) or regional scale (e.g., Brusa et al., 2017a). The habitat definition typically involves plant communities defined at the phytosociological alliance level (Evans, 2006). However,

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habitats interpretation has been broad rather than strict. As a result, some plant communities or environmental features that were not strictly related to the official definition may have been included in the same habitat to protect ecosystems that did not qualify as Annex I habitats (Evans, 2006; 2010), potentially giving rise to misleading assessments of conservation status. Extensive habitats interpretations and extreme situations should be carefully checked and identified prior to comparing them to Favourable Reference Values (FRVs) set for the correct standard of the same habitat.

As a case study, we considered the species-rich *Nardus stricta* grasslands (habitat 6230*), which interpretation raised several issues in many EU countries and regions (Evans, 2010). This priority habitat type is widespread in the EU, occurring in 24 Member States (MS), as well as in Norway, Switzerland and the United Kingdom (Delarze et al., 2015; Fremstad, 2002), and six biogeographic regions (Galvánek and Janák, 2008). Among the MS, Italy shows the largest habitat 6230* area within the N2K network, mainly in the Alpine biogeographic region (https://nature-art17.eionet.europa.eu/article17/habitat/summary/?period=5&group=Grasslands&subject=6230&region=), greatly referable to the Lombardy administrative region, which occupies a central position in the southern Alps (https://eunis.eea.europa.eu/habitats/10122). Despite its wide distribution, habitat 6230* is undergoing a decrease in area across various biogeographic regions (Peppler-Lisbach et al., 2020) and European mountain ranges (Macdonald et al., 2000; Prévosto et al., 2011). The habitat 6230* conservation status is Unfavourable-bad (U2) in five biogeographic regions and Unfavourable-inadequate (U1) in the Alpine region (EEA, 2021a), and it is listed as "vulnerable" in the European Red List of Habitats being threatened by management intensification and land abandonment (Janssen et al., 2016; https://forum.eionet.europa.eu/european-red-list-habitats/library/terrestrial-habitats/e.-grasslands/e1.7-lowland-submontane-dry-mesic-nardus-grassland-1/).

Habitat 6230* is officially defined as "Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas (and sub-mountain areas, in Continental Europe)". The interpretation manual of EU habitats (EC, 2013) provides further details, defining it as "closed dry or mesophile, perennial *Nardus* grasslands occupying siliceous soils in Atlantic or sub-Atlantic or boreal lowland, hill and montane regions". The geographic discrimination of habitat 6230* is of lesser concern, given its wide distribution across many MS and biogeographic regions. Strict compliance is necessary for correctly identifying abiotic and biotic features, especially substrate, elevation, and species richness. Therefore, it is presumable that if the definition of the habitat is excessively extended concerning one or more of these points, the assessment of its conservation status is likely to be compromised.

Although referring only to siliceous substrates, it is now widely accepted that the habitat 6230* can also occur on leached carbonate substrates (Leuschner and Ellenberg, 2017), as has been reported in different MS (Bensettiti et al., 2005; Lüth et al., 2011; Stanová and Valachovič, 2022), including Italy (Biondi et al., 2012; Gennai et al., 2014). However, it is worth remembering that maintaining habitat 6230* on carbonate substrates is at risk since this kind of grassland might quickly evolve into more eutrophic meadows (Carroll et al., 2003), which can no longer be included in the definition of this habitat. The occurrence of habitat 6230* should be limited to sites located below the potential treeline (Galvánek and Janák, 2008), as indicated by terms such as "montane", "submontane", "hill", and "boreal lowland". Its frequency should at least be conspicuous only in lowlands of Atlantic and Boreal Europe or in mountain areas of Continental Europe, including the major mountain ranges (e.g., Alps, Pyrenees, Apennines, Dinarides, Carpathians and Scandinavian mountains). Hence, grazed grasslands of the alpine belt, commonly of primary origin, should be referred to other habitats (e.g., habitat 6150 "Siliceous alpine and boreal grasslands"), even if *Nardus* is present or dominant (Ellmauer, 1993; Grabherr, 1993). Lastly, species richness is another remarkable feature of the habitat 6230*; therefore, over-grazed grasslands notoriously associated with *Nardus* dominance and floristic degradation (Armstrong et al., 1997; Gennai et al., 2014) should not be included in this habitat. Moreover, pastures which have become irreversibly damaged through over-grazing should also be excluded (EC, 2013).

Based on such considerations, the Italian Alps' subalpine grasslands straddling the treeline are more prone to a misleading habitat 6230* interpretation, potentially worsening the outcomes of regional conservation status assessment. In this region, the treeline varies greatly due to continentality, geomorphology and land use (Caccianiga et al., 2008). At higher elevations, substrates can often be calcareous with shallow soils, as opposed to lower elevations where acidic soils may come from previous deforestation followed by long-lasting grazing activities other than from acidic bedrock. Moreover, over-grazed grasslands are now mainly located at higher elevations due to land use changes linked to a generalized dereliction of the lower areas. Therefore, the present study aims, focusing on the subalpine habitat sub-type at the regional scale, 1) to evaluate whether the spatial distribution of habitat 6230* within the N2K sites of the Lombardy region (northern Italy, central southern Alps) corresponds to the abiotic features (substrate and elevation) that are essential for its identification, and 2) to quantify the effects of interpretation extensions beyond its definition on outcomes of regional conservation status assessments. Specifically, we analyzed the habitat 6230* spatial distribution regarding the elevation range, the geological substrate, its position concerning the treeline, its coherence with herbaceous physiognomy and its contacts with other habitats. We then tested the effects of habitat interpretation extensions beyond its definition on outcomes of conservation status assessments by calculating a set of indicators concerning structure and functions, using floristic-vegetation relevés referable to the habitat 6230* reported in the literature before the entry into force of the HD (years 1950–1980), which potentially can be the base to derive FRVs.

2. Methods

2.1. Spatial distribution analysis

Spatial analysis was carried out using QGIS software (version 3.10.11). The HD Art. 17 requires MS to draw up a six-yearly report on the measures taken under the HD, including updates about habitat occurrence. We thus used the most recent habitat occurrence map of the Lombardy administrative region (northern Italy, central southern Alps) based on the results of the IV report ex-art. 17 (available online at https://www.geoportale.regione.lombardia.it/) and on a modelling approach (Dalle Fratte et al., 2019), respectively, within and outside the N2K network. All other maps we used were available online at the geoportal of Lombardy (https://www.geoportale.regione.lombardia.it/): i) the digital elevation model of Lombardy (raster; 20 × 20 m resolution); ii) the map of lithological substrates (shapefile; 6 classes: silicate rocks, carbonate rocks, alluvial deposits, recent western moraines, recent eastern moraines, other moraine deposits); iii) the regional map of land use types (DUSAF v.6, shapefile; 78 classes based on Corine Land Cover classification); iv) the map of forest types (PIF v.2019, shapefile; 231 classes). All maps were retrieved on 20/11/2021, and shapefiles were converted into raster format (20 × 20 m resolution) for the subsequent analysis.

For each polygon attributed to the habitat 6230* within the N2K network, we calculated the average elevation, area, and the most widespread lithological substrate using the function "zonal statistics". To compare the distribution of habitat 6230* with the forest treeline, we created for each polygon of habitat 6230* a 100 m buffer that we intersected with the map of forest types. We considered the polygons placed within 100 m of forested areas to be below the current forest treeline. We classified the other polygons considering their elevation: below the forest treeline if lower than 1300 m a.s.l. and above the forest treeline if higher than 1800 m a.s.l.. We further checked by photointerpretation the remaining polygons between 1300 and 1800 m a.s.l., which is the elevation range with the highest forest treeline dynamics (Caccianiga et al., 2008). We then intersected the habitat 6230* map with the regional map of land use types to calculate, for each polygon of the habitat 6230*, the percentage of land use types with herbaceous physiognomy, i.e. corresponding to one or more of these classes: 2311 - permanent meadows without trees and shrubs, 2312 - permanent meadows with sparse trees and shrubs, 3211 - natural high altitude grasslands without trees and shrubs, 3212 - natural high altitude grasslands with sparse trees and shrubs, 333 - sparse vegetation. We calculated classes of herbaceous physiognomy using the 20 % increments. Finally, we added a 10 m buffer to each habitat 6230* polygon within the N2K network and intersected it with the habitats map of Lombardy to analyse contacts with other habitats.

2.2. Threshold values identification and conservation status assessment

The habitat database of the Lombardy region contains 142 floristic-vegetation relevés referred to the habitat 6230* (Brusa et al., 2017b). In the regional territory of Lombardy, the habitat 6230* has been divided into three habitat sub-types according to their floristic variation with elevation and considering the associated syntaxa (Bonari et al., 2023; EC, 2013): 6230*-A, lowland and hill grasslands (n = 16); 6230*-B, montane grasslands (n = 22); 6230*-C, subalpine grasslands (n = 104) (Table 1).

We investigated the effects of interpretation extensions beyond habitat definition on outcomes of conservation status assessment focusing on plant communities at the ecological extremes of the subalpine habitat sub-type 6230*-C (hereafter “plant communities at the extremes”). These plant communities are prevalent in northern Italy, making an extension of habitat interpretation more likely (Bonari et al., 2023). We identified only the relevés of *Nardetum alpigenum* on silicate substrates (=*Geo montani-Nardetum*) (n = 40; Giacomini et al., 1962) as target relevés of the habitat sub-type 6230*-C (EC, 2013). We compared indicator values (Table 2) of different sets of relevés belonging to plant communities at the extremes with thresholds calculated on the target relevés of the habitat sub-type 6230*-C. We considered as plant communities at the extremes: i) subalpine *Nardus* grasslands on carbonates substrates (*Nardetum alpigenum* on carbonate substrates, n = 8; Andreis and Rodondi, 1982); ii) subalpine *Nardus* grasslands on nutrient-rich soils (*Nardetum alpigenum trifolietosum*, n = 11; Gerdol and Piccoli, 1980); iii) high-grazed alpine *Nardus* grasslands (*Festucetum halleri nardetosum*, n = 25; Giacomini and Pignatti, 1955); iv) low-grazed alpine *Nardus* grasslands (*Caricetum curvulae nardetosum strictae*, n = 7; Caccianiga et al., 2000).

Table 1
Overview of habitat 6230* subtypes of Lombardy region in relation to CORINE Biotopes and EUNIS 2021 classification codes (Devillers et al., 1991; EEA, 2021b). The syntaxa refers to the classification of Mucina et al. (2016).

Subtype	Description	Syntaxa	CORINE Biotopes	EUNIS 2021
6230*-A	Meso-subxerophytic oligotrophic grasslands in the lowland to submontane belt of the sub-Atlantic regions of western and central Europe, subject to grazing or regular mowing without fertilization	*Violion caninae* Schwickerath 1944	35.11 Mat-grass swards	R1M1 *Nardus stricta* swards
6230*-B	Dry and oligotrophic pastures in the montane belt of the Alps	*Nardo-Agrostion tenuis* Sillinger 1933 *Nardo-Agrostion caninae* Cortini-Pedrotti et al. 1973	35.11 Mat-Grass swards	R1M1 *Nardus stricta* swards
6230*-C	Chionophilous grasslands in the subalpine belt of the Alps, usually subject to grazing	*Nardion strictae* Br.-Bl. 1926	36.311 Pyreneo-Alplne mesophile mat-grasslands	R4311 Pyreneo-Alpine mesophile mat-grass swards

Table 2
List of indicators for structure, functions, and future prospects of the habitat 6230*.

Type	Indicator	Description
Structure	Total coverage (%)	Sum of the coverage of all species present in each relevé.
	Floristic richness (n)	Number of species present in each relevé (excluding trees, shrubs, and species with N-Landolt ≥ 4).
	Dominance of typical species (%)	Ratio between the sum of the coverage of typical species and the sum of the coverage of all species in each relevé.
Functions	Frequency of typical species (%)	Ratio between the number of typical species and the number of all species in each relevé.
	Early warning species (n)	Number of early warning indicator species in each relevé.
	Significant species for conservation (n)	Number of significant species for conservation present in each relevé: i.e., those reported in Annexes II and IV of the Habitats Directive, in the Red List of threatened vascular plants in Italy (Orsenigo et al., 2021), and in the list of regional protected species (Lombardy region law n. 10/2008).
Future prospects	Woody encroachment (%)	Ratio between the sum of the coverage of trees and shrubs, and the sum of the coverage of all species.
	Eutrophication (%)	Ratio between the sum of the coverage of species indicators of eutrophication (N-Landolt ≥ 4), and the sum of the coverage of all species.
	Floristic degradation (%)	Coverage of *Nardus stricta* in each relevé.

For each plant community at the extremes, we calculated structure and functions indicators of the habitat 6230* based on the floristic-vegetation relevés (Table 2), like those determined for other habitats (Del Vecchio et al., 2016; Carli et al., 2016; Kovač et al., 2016). We associated each species with its corresponding life form (Pignatti et al., 2017), eutrophication and conservation value. We considered species indicators of eutrophication to be those with N-Landolt value ≥ 4 (Landolt et al., 2010). We selected species important for conservation value based on their listing on Annexes II and IV of the HD, Red List of threatened vascular plants in Italy (Orsenigo et al., 2021), and list of regional protected species (Lombardy region law n. 10/2008).

We defined the list of typical species, including early warning indicators, through the functional-based diagnostic species approach using Grime’s CSR and dark diversity (Grime, 2006; Dalle Fratte et al., 2022). To this aim, we assembled Grime’s CSR plant strategy scores of each species using the existing database of functional traits of Northern Italy (Cerabolini et al., 2010; Dalle Fratte et al., 2021). We excluded trees and shrubs, i.e., (nano)phanerophytes, and species with N-Landolt ≥ 4 for calculating floristic richness, frequency and dominance of typical species, since we used these species as indicators respectively of woody encroachment and eutrophication (Table 2).

Since plant communities at the extremes refer to specific sites, their assessment should use the term “degree of conservation” according to the explanatory notes to the N2K Standard Data Form (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32011D0484:EN:NOT). Yet, we used here the protocol and terminology from the regional assessment as our goal was to identify the potential effects on the assessment of the regional conservation status when including such extreme situations. Following the methodologies proposed for the habitats of France (Carnino, 2009; Maciejewski et al., 2016), we calculated the threshold values of conservation status by dividing the score distribution of each indicator in percentiles (Fig. 1) to get three intervals corresponding to Favourable (FV), Unfavourable-inadequate (U1), Unfavourable-bad (U2). FV indicates that the habitat can thrive without management changes; U1 and U2 indicate that the habitat require management policies changes, respectively, not being or being at risk of extinction (EC, 2023). We set the 50th percentile threshold to discriminate FV from U1, and the 10th percentile to differentiate U1 from U2, or the 90th percentile, in case of future prospect indicators.

We identified more thresholds for the floristic degradation indicator (i.e., *Nardus* coverage), considering that *Nardus* coverage is essential for identifying habitat 6230* but also indicates habitat degradation when dominant (Galvánek and Janák, 2008). Therefore, we assigned FV to the *Nardus* coverage within the interquartile range (25th – 75th percentiles), and we used both the 10th and 90th percentiles to discriminate U1 from U2 (Fig. 1).

Prior to analyses we converted cover-abundance data to percentage using the mean values of the interval classes as follow: r = 0.1, + = 0.5, 1 = 6.75, 2 = 18.75, 3 = 37.5, 4 = 62.5, 5 = 87.5 (Zanzottera et al., 2020). The nomenclature of each taxon in the dataset was standardized according to Bartolucci et al. (2018).

2.3. Statistical analysis

All the statistical analyses were performed using the R software (R core team, 2021). We evaluated the differences in polygons average elevation and area between siliceous and calcareous substrates, as well as above and below the treeline through the Wilcoxon test, using the "wilcox.test" function of the base R package "stats". We then compared the differences in area and elevation along the classes of herbaceous physiognomy of polygons through Dunn's test multiple comparisons, using the function "dunn.test" of the package "dunn.test" (Dinno, 2017).

To compare plant communities at the extremes with the target relevés of habitat subtype 6230*-C, we used the Wilcoxon test with the following sequence: 1) we checked whether the values were significantly higher than the FV threshold, 2) if they were not, we checked whether they were significantly lower than the FV threshold and higher than the U1 threshold, 3) alternatively, we verified whether they were significantly lower than the U2 threshold.

3. Results

3.1. Spatial distribution analysis

Within the N2K network of the Lombardy region, there were significantly more polygons of habitat 6230* on siliceous substrates (n = 1364) than on carbonate ones (n = 62), the latter being placed at significantly lower altitudes (Fig. 2a). At the same time, the number of polygons below the treeline (n = 1178) was four times greater than those placed above the treeline (n = 248), which average elevation significantly differed as expected (Fig. 2b). The average area of polygons did not differ concerning substrate type and forest treeline (Fig. 2c and 2d).

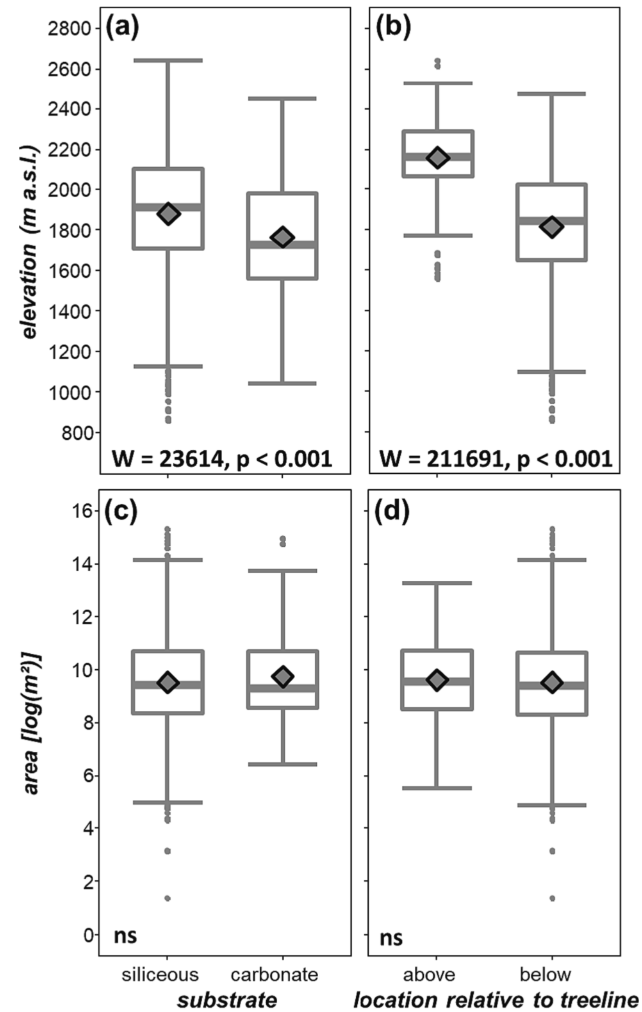

Fig. 2. Average elevation (a, b) and area (c, d) of polygons of the habitat 6230* within the N2K network of Lombardy region in relation to substrate (a, c) and forest treeline (b, d). The significance of the Wilcoxon test comparison is reported in each figure (ns = not significant). Boxplots indicate the mean (diamond), median (line in the middle of the boxes), interquartile range (boxes), ± 1.5 times the interquartile range (whiskers) and outliers (circles).

The two land use classes that best matched the surface covered by the habitat 6230* were "3211 - permanent grasslands of high elevation without shrubs and trees" (59.1 %) and "333 - sparse vegetation" (15.5 %) (Fig. 3a). Other herbaceous land use classes were less represented, such as "2311- permanent meadows without shrubs and trees" (4.4 %) and "3212 - permanent grasslands of high elevation with shrubs and

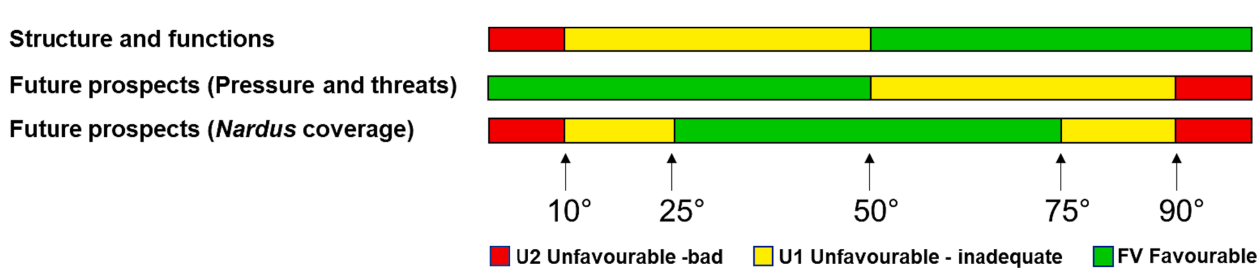

Fig. 1. Identification of threshold values of conservation status along the score distribution of the indicators of structure and functions, and future prospects (represented by pressures and threats and the *Nardus* coverage).

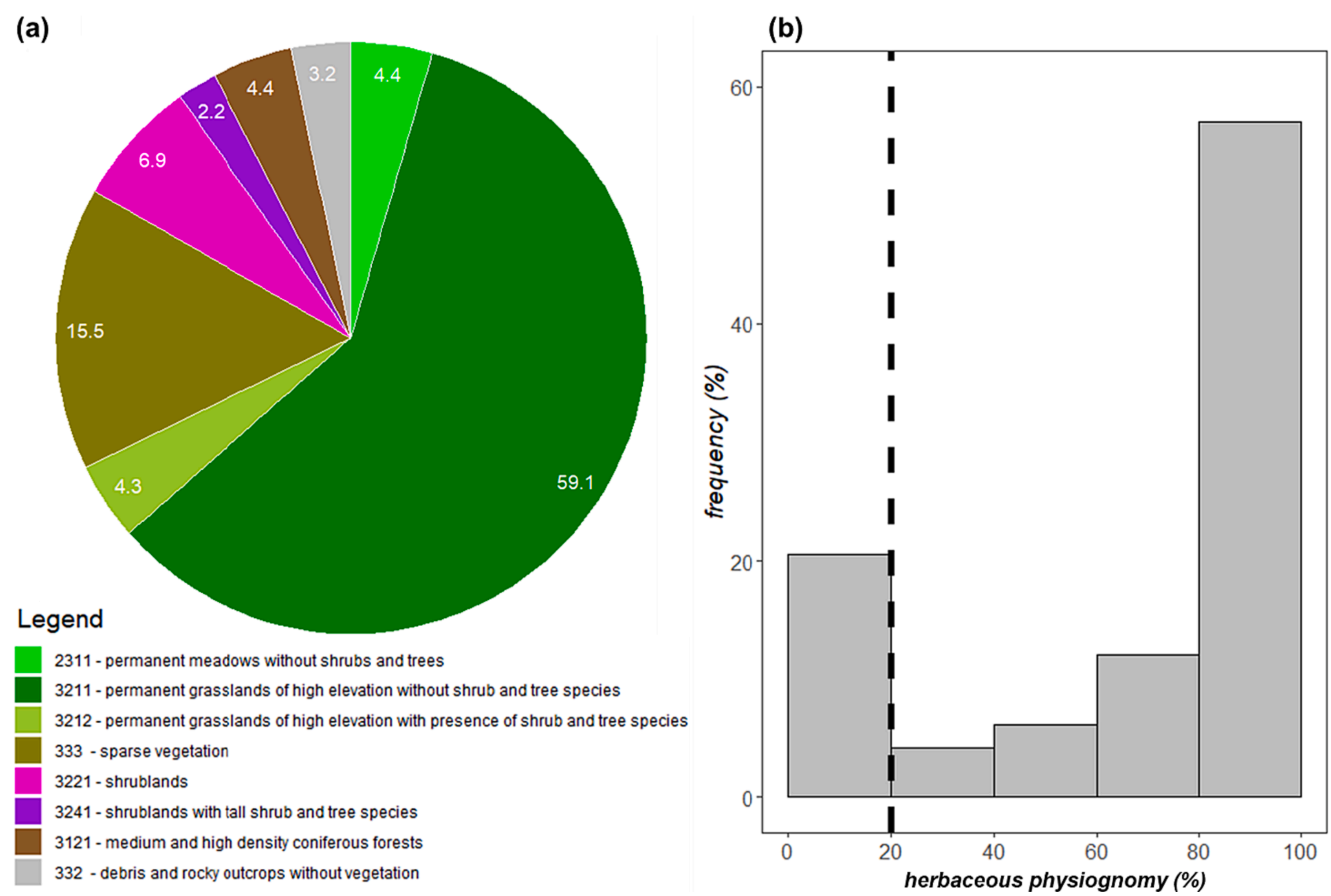

Fig. 3. Main classes of land use types (>2 %) corresponding to the habitat 6230* occurrence within the N2K network of Lombardy region (a), and relative frequency of polygons for the classes indicating increasing percentage of land use types representing herbaceous physiognomy of the habitat 6230* (b). The dashed line indicates the first decile.

trees" (4.3 %). Moreover, the habitat 6230* overlapped with a rather significant percentage of woody land use classes, such as "3221 – shrublands" (6.9 %), "3121 - medium and high-density coniferous forests" (4.4 %), "3241 - shrubland with tall shrubs and trees" (2.2 %), and also non (or scarcely) vegetated land use classes, i.e., "332 - debris and rocky outcrops without vegetation" (3.2 %) (Fig. 3a).

Most of the habitat 6230* polygons were characterized by high herbaceous physiognomy (>80 %) (n = 813; Fig. 3b). Fewer polygons showed moderate or low herbaceous physiognomy: between 60 % and 80 % (n = 173), between 40 % and 60 % (n = 88), and between 20 % and 40 % (n = 59) (Fig. 3b). On the contrary, we observed many polygons with a poor herbaceous physiognomy (<20 %) (n = 293) (Fig. 3b).

Polygons with poor herbaceous physiognomy had a significantly lower average elevation than the others, contrary to those with high herbaceous physiognomy, which showed the highest elevation (Fig. 4a). Polygons with intermediate values of herbaceous physiognomy (between 20 % and 80 %) had a similar average elevation (Fig. 4a). At the same time, polygons with poor herbaceous physiognomy were significantly smaller than the others, which average area was almost similar to each other (Fig. 4b). Only the polygons with high herbaceous physiognomy were significantly smaller than those characterized by moderate herbaceous physiognomy (between 60 % and 80 %) (Fig. 4b).

The habitat 6230* was mostly in contact with habitats 6150 "Siliceous alpine and boreal grasslands" and 4060 "Alpine and Boreal heaths", respectively for 19.4 % and 24.8 % of cases (Fig. 5). Most of the remaining contacts were with other shrubland and forest habitats (31.7 %), in particular with forests of the habitats 9410 "Acidophilous *Picea* forests of the montane to alpine levels (*Vaccinio-Piceetea*)" (11.8 %) and 9420 "Alpine *Larix decidua* and/or *Pinus cembra* forests" (15.2 %), and to a lesser extent with habitats 6430 "Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels" (5.7 %) and 7140 "Transition mires and quaking bogs" (4.6 %) (Fig. 5). Finally, the habitat 6230* emerged to be in contact with siliceous screes or rock outcrops, such as habitats 8110 "Siliceous scree of the montane to snow levels (*Androsacetalia alpinae* and *Galeopsetalia ladani*)" (8.6 %) and 8120 "Calcareous and calcshist screes of the montane to alpine levels (*Thlaspietea rotundifolii*)" (5.1 %) (Fig. 5).

3.2. Conservation status of plant communities at the extremes

The list of typical and early warning indicator species for the target relevés of the habitat sub-type 6230*C in Lombardy is reported in Table 3. Overall, we derived 48 typical species, among which nine were early warning indicators. As it could be expected, the plant communities at the extremes never displayed the whole list of typical species (Table 3). However, subalpine *Nardus* grasslands on carbonate substrates and high-grazed alpine ones (*Festucetum halleri nardetosum*) showed more typical species, respectively n = 22 and n = 32. On the contrary, subalpine *Nardus* grasslands on nutrient-rich soils (*Nardetum alpigenum trifolietosum*) and low-grazed alpine ones (*Caricetum curvulae nardetosum strictae*) displayed a lower number of typical species, respectively n = 17 and n = 19 (Table 3). The number of observed early warning indicator species was always low in all plant communities at the extremes, ranging from two to three (Table 3). Finally, only four typical species, other than *Nardus*, were common to all plant communities at the extremes: *Geum montanum*, *Lotus corniculatus* subsp. *corniculatus*,

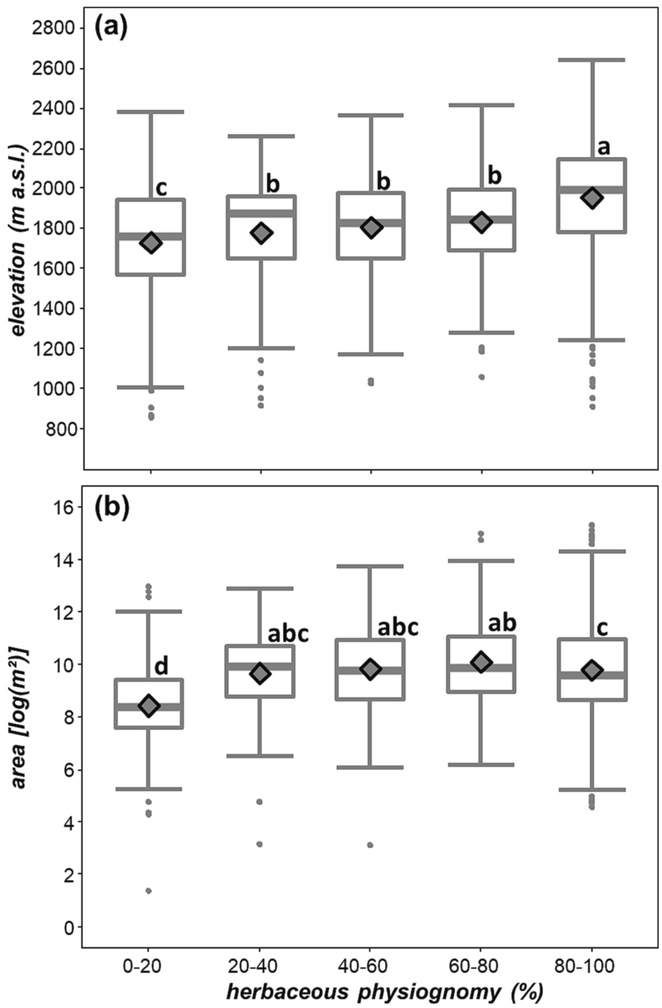

Fig. 4. Average elevation (a) and area (b) of polygons of the habitat 6230* within the N2K network of Lombardy region in relation to the percentage of herbaceous physiognomy. Small letters indicate the results of the Dunn test post-hoc comparisons at $p < 0.05$. Boxplots indicate the mean (diamond), median (line in the middle of the boxes), interquartile range (boxes), ± 1.5 times the interquartile range (whiskers) and outliers (circles).

Potentilla aurea subsp. *aurea*, *Soldanella alpina* subsp. *alpina* (Table 3).

The threshold values of conservation status identified for the indicators of structure, functions, and future prospects for the target relevés of the habitat sub-type 6230*-C are reported in Table 4. According to the precautionary principle, the global conservation status was U2 for all plant communities at the extremes (Table 5 and Fig. 6). However, the conservation status showed different patterns for each indicator and for each plant community at the extremes. The indicators of total coverage, presence of significant species, and woody encroachment showed a FV conservation status in half of the plant communities at the extremes (n = 2; Table 5 and Fig. 6). Only two indicators (i.e., early warning species and eutrophication) never showed FV conservation status; the conservation status resulted as U1 for all plant communities at the extremes (Table 5 and Fig. 6). The dominance and frequency of typical species had the worst performances, indicating U2 conservation status in three plant communities at the extremes. Remarkably, none of the indicators showed FV or U2 conservation status for all plant communities at the extremes (Table 5 and Fig. 6). The subalpine grasslands on carbonate substrates showed the highest number of indicators with U1 conservation status (n = 5) and the lowest number of indicators with U2 conservation status (n = 2) (Table 5 and Fig. 6), while those on nutrient-rich soils showed the highest number of indicators with FV conservation status (n = 4) (Table 5 and Fig. 6). The low-grazed alpine grasslands showed the worst conservation status represented by seven indicators with U2 and none in FV conservation status (Table 5 and Fig. 6).

4. Discussion

Concerning our first aim, we observed a distinct pattern of the habitat 6230* spatial distribution within the N2K network of the Lombardy region that did not fully correspond to substrate and elevation features that are essential for identifying it. Most polygons were located on siliceous substrates and below the forest treeline, in accordance with the habitat 6230* definition (EC, 2013). However, several polygons were located on carbonate substrates and above the treeline, representing plant communities at the extremes. The presence of polygons in situations beyond a rigorous definition of the habitat 6230* can be likely due to its difficult ecological interpretation combined with several syntaxonomic drawbacks (Bonari et al., 2023; Evans, 2010). The phytosociological classification of *Nardus* grasslands has long been problematic due to their wide variation. These are anthropogenic plant communities that can origin in different ways across their geographical and altitudinal range while preserving floristic traces of their original natural composition (e.g., Gennai et al., 2014; Lüth et al., 2011; Mucina et al., 2016).

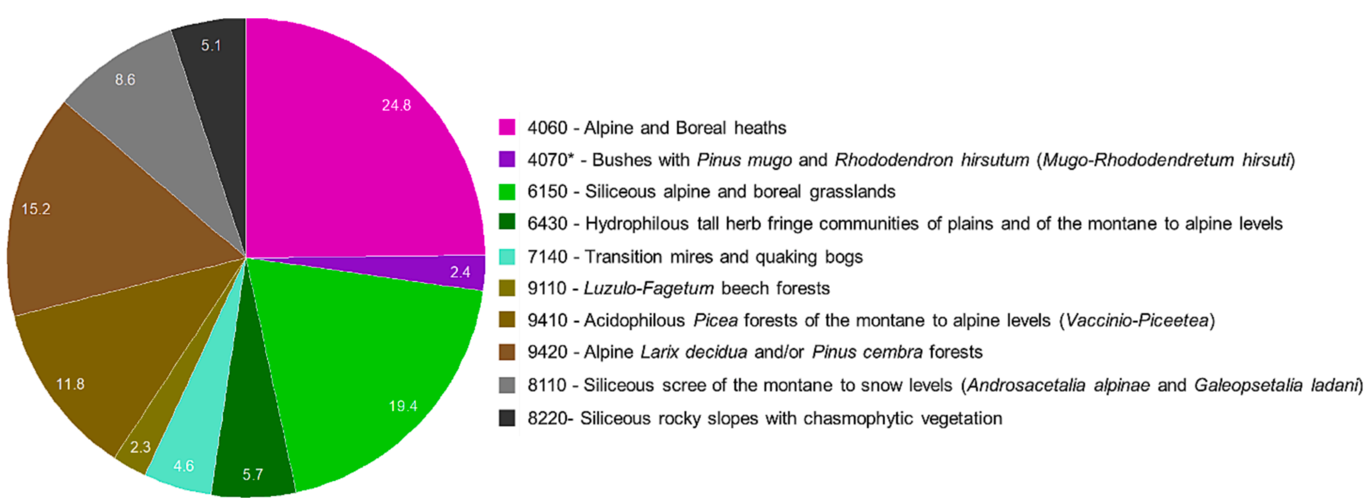

Fig. 5. Main contacts (>2 %) between the polygons of the habitat 6230* within the N2K network of Lombardy region and other habitats.

Table 3
List of typical and early warning indicator species (marked with an asterisk) of the target relevés of the habitat sub-type 6230*-C (*Geo montani-Nardetum*) and their presence in the plant communities at the extremes: subalpine carbonate (*Nardetum alpigenum* on carbonate substrates); subalpine high-nutrient (*Nardetum alpigenum trifolietosum*); alpine high-grazed (*Festucetum halleri nardetosum*); alpine low-grazed (*Caricetum curvulae nardetosum strictae*).

6230*-C target	6230*-C target	Subalpine carbonate	Subalpine high nutrient	Alpine high-grazed	Alpine low-grazed
Achillea erba-rotta subsp. *moschata*	X				
Agrostis rupestris subsp. *rupestris*	X			X	X
Ajuga pyramidalis	X				
Antennaria dioica	X	X	X	X	
Campanula barbata	X	X	X	X	
Carex pallescens	X	X	X		
Carex sempervirens subsp. *sempervirens*	X	X		X	X
Cerastium arvense subsp. *strictum*	X		X	X	
Daphne striata	X			X	
Euphrasia hirtella	X				
Euphrasia minima	X	X		X	X
Festuca rubra subsp. *rubra*	X	X	X	X	
Galium anisophyllon	X	X		X	
Gentiana acaulis	X	X		X	X
Geum montanum	X	X	X	X	X
Hieracium alpinum	X			X	
Homogyne alpina	X	X		X	X
Leucanthemopsis alpina subsp. *alpina*	X	X		X	X
Lotus corniculatus subsp. *corniculatus*	X	X	X	X	X
Luzula spicata subsp. *conglomerata*	X		X	X	
Luzula sudetica	X			X	
Mutellina adonidifolia	X			X	X
Nardus stricta	X	X	X	X	X
Omalotheca sylvatica	X				
Phyteuma hemisphaericum	X	X		X	X
Pilosella lactucella	X	X	X		
Plantago atrata subsp. *atrata*	X		X		
Potentilla aurea subsp. *aurea*	X	X	X	X	X
Scorzoneroides helvetica	X	X		X	X
Sempervivum montanum subsp. *montanum*	X			X	
Sibbaldia procumbens	X			X	X
Silene acaulis s.l.	X			X	X
Silene nutans subsp. *nutans*	X		X		
Silene vulgaris s.l.	X				
Soldanella alpina subsp. *alpina*	X	X	X	X	X
Thymus praecox subsp. *polytrichus*	X		X	X	
Trifolium alpinum	X	X		X	X
Trifolium thalii	X				
Veronica bellidioides	X			X	
Early warning indicators					
Cardamine resedifolia	X			X	
Deschampsia cespitosa	X		X	X	X
Festuca rubra subsp. *commutata*	X				
Gentianella campestris subsp. *campestris*	X				
Helictochloa versicolor subsp. *versicolor*	X	X		X	X
Leontodon hispidus subsp. *hispidus*	X	X	X		
Pilosella hoppeana	X	X			
Potentilla crantzii subsp. *crantzii*	X				
Veronica fruticans	X				

Table 4
Threshold values of conservation status identified for the indicators of structure, functions and future prospects according to the percentile analysis (see also Figure 6) for the target relevés of the habitat sub-type 6230*-C (*Geo montani-Nardetum*). The full description of each indicator is reported in Table 2. Legend: U2 = Unfavourable-bad, U1 = Unfavourable-inadequate, FV = Favourable.

Type	Indicator	U2	U1	FV
Structure	Total coverage (%)	< 101	≥ 101	≥ 123
	Floristic richness (n)	< 27	≥ 27	≥ 38
	Dominance of typical species (%)	< 61	≥ 61	≥ 81
Functions	Frequency of typical species (%)	< 49	≥ 49	≥ 57
	Early warning species (n)	$= 0$	> 0	≥ 2
	Significant species for conservation (n)	< 2	≥ 2	≥ 3
Future prospects	Woody encroachment (%)	≥ 9	≥ 1	< 1
	Eutrophication (%)	≥ 15	≥ 4	< 4
	Floristic degradation (%)	$< 19 \cup \geq 88$	$< 38 \cup \geq 63$	$\geq 38 \cap < 63$

Nardus grasslands referred the habitat 6230* are typical semi-natural grasslands on acidic soils in most of temperate Europe, so that they are included in the "acidic grasslands" (e.g., Duprè et al., 2010). However, in some countries, this habitat is also found on leached calcareous substrates, where the calcium content is low in the upper layers of the soil because of high precipitation (Bensettiti et al., 2005, Biondi et al., 2010; Galvánek and Janák, 2008; Stanová and Valachovič, 2022). Although we can't certainly state whether the polygons of habitat 6230* on carbonate substrates were subject to leaching, our work can help detect areas for more targeted verification and monitoring. Our results underlined that floristic richness, dominance and frequency of typical species are lower on carbonate substrates compared to the target subalpine grasslands, resulting in U2 conservation status. Such differences should be related to the highest proportion of calcicolous species on carbonate substrates. Contrary to Pittarello et al. (2017), we haven't found a higher floristic richness on carbonate substrates, likely because

Table 5
Conservation status of the plant communities representing ecological extremes of the subalpine habitat sub-type 6230*-C: subalpine carbonate (*Nardetum alpigenum* on carbonate substrates); subalpine high-nutrient (*Nardetum alpigenum trifolietosum*); alpine high-grazed (*Festucetum halleri nardetosum*); alpine low-grazed (*Caricetum curvulae nardetosum strictae*). The full description of each indicator is reported in Table 2. Legend: U2 = Unfavourable bad; U1 = Unfavourable inadequate; FV = Favourable.

Type	Indicator	Subalpine carbonate	Subalpine high nutrient	Alpine high-grazed	Alpine low-grazed
Structure	Total coverage (%)	FV	U2	FV	U1
	Floristic richness (n)	U1	FV	U2	U2
	Dominance of typical species (%)	U2	U2	U1	U2
Functions	Frequency of typical species (%)	U2	U2	FV	U2
	Early warning species (n)	U1	U1	U1	U1
	Significant species for conservation (n)	FV	FV	U2	U2
Future prospects	Woody encroachment (%)	FV	U1	FV	U2
	Eutrophication (%)	U1	U1	U1	U1
	Floristic degradation (%)	U1	FV	U1	U2
OVERALL		U2	U2	U2	U2

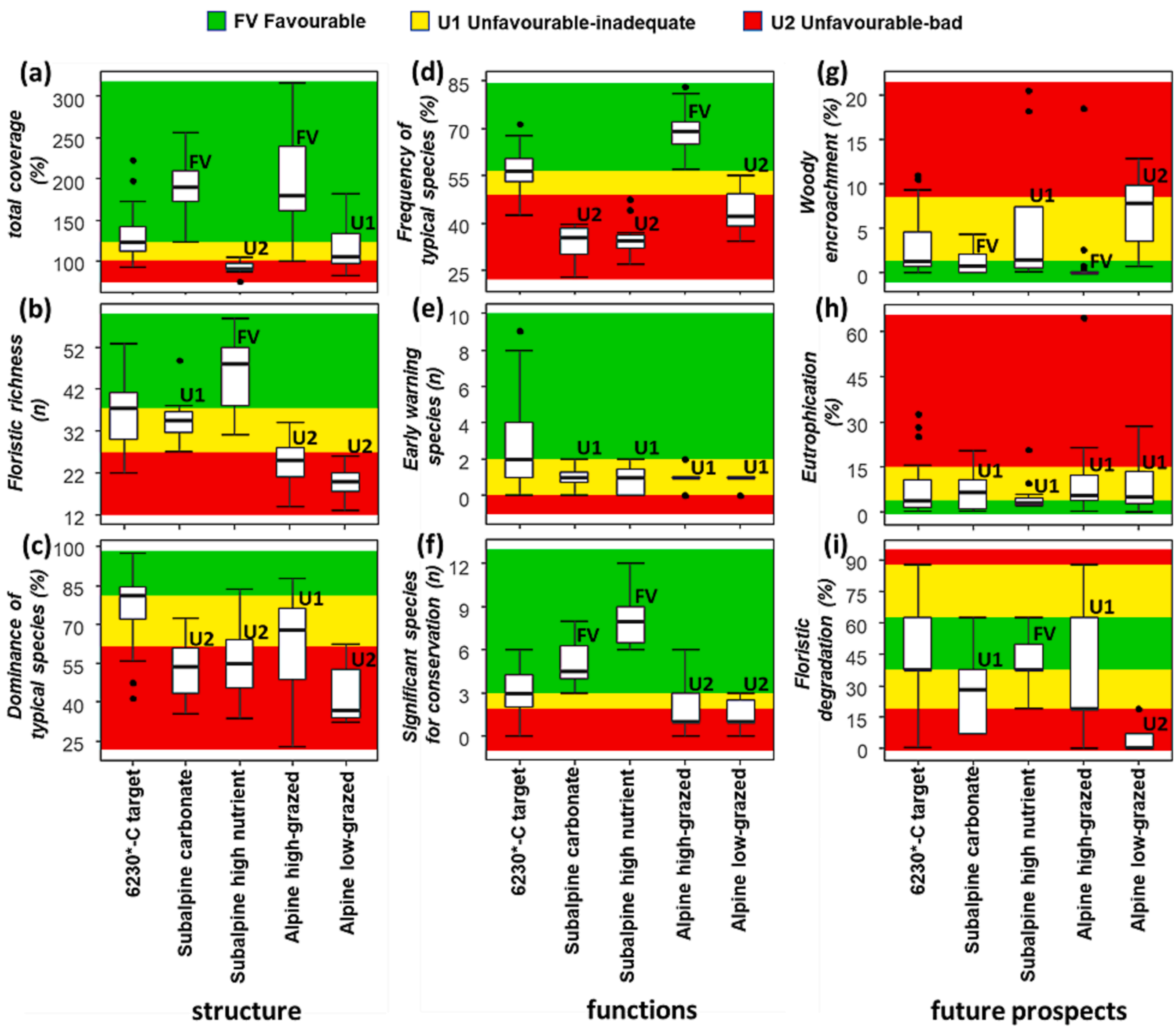

Fig. 6. Comparison between the threshold values of conservation status identified for the indicators of structure, functions and future prospects of the target relevés of the habitat sub-type 6230*-C (*Geo montani-Nardetum*) and those calculated for plant communities at the extremes: subalpine carbonate (*Nardetum alpigenum* on carbonate substrates); subalpine high-nutrient (*Nardetum alpigenum trifolietosum*); alpine high-grazed (*Festucetum halleri nardetosum*); alpine low-grazed (*Caricetum curvulae nardetosum strictae*). The full description of each indicator is reported in Table 2. Boxplots indicate the median (line in the middle of the boxes), interquartile range (boxes), ± 1.5 times the interquartile range (whiskers) and outliers (circles).

they included a broad set of plant communities with different degrees of leaching and acidification. At the same time, *Nardus* grasslands on carbonate substrates showed a higher degree of eutrophication, confirming the importance of this driver of floristic change for calcareous grasslands (Newton et al., 2012).

Furthermore, habitat 6230* has a high variability with elevation since it can be present from the lowlands in Atlantic Europe to subalpine areas in European mountains (Galvánek and Janák, 2008). In Italy, *Nardus* grasslands are mostly found in the Alps (Gennai et al., 2014; Lüth et al., 2011), but this should not justify the presence of habitat 6230* in the alpine belt. The *Nardus* grasslands of the lower alpine belt should be carefully treated since they are mainly natural grasslands which keep their primary origin (habitat code 61xx). When these grasslands are used as pastures, *Nardus* can often determine the physiognomy of the vegetation (Fischer and Wipf, 2002), even if they should not be regarded as proper semi-natural grasslands (habitat code 62xx). Our results suggest that this difference may have been overlooked, which could lead to overestimating the distribution of habitat 6230* at a higher elevation. Concerning the floristic richness indicator, the alpine sets of relevés indicated U2 conservation status, thus confirming that, in *Nardus* grasslands, the species richness negatively correlates with elevation (Parolo et al., 2011). On the contrary, in the subalpine belt, the species richness is higher, probably because there is an overlap between the montane and alpine species pool (Maurer et al., 2006). This evidence highlights the importance of excluding alpine plant communities from habitat 6230* to preserve the high species richness that characterizes this habitat, especially in the case of more or less intense grazing (EC, 2013; Evans, 2010; Galvánek and Janák, 2008).

Considering our second aim, we found clear evidence that including plant communities at the extremes negatively affected the regional conservation status assessment. Through the indicator analysis, we were able to evaluate the effects on the floristic richness, which is a fundamental feature of the habitat 6230*, and consequently also on the frequency and dominance of typical species, including early warning ones (Dalle Fratte et al., 2022). Only for subalpine high-nutrient *Nardus* grasslands, the indicator of floristic richness resulted in FV conservation status, likely because under high-nutrient conditions, an initial increase of species richness could be expected due to the entry of nitrophilous plant species associated with livestock dejection (Parolo et al., 2011). However, eutrophication is one of the main threats to the habitat 6230* (Galvánek and Janák, 2008), and can have severe negative impacts, leading to species-poor or common eutrophic vegetation communities no longer attributable to the habitat (Peppler-Lisbach et al., 2020; Stevanović et al,. 2008; Tasser and Tappeiner, 2002). Other adverse effects on the regional conservation status assessment were observed for species significant for conservation, woody encroachment and floristic degradation in alpine grasslands, especially low-grazed facets. Therefore, their conservation status should be evaluated using indicators based on focal relevés of other habitats to which they most likely belong, such as those most frequently contacted (e.g., 6150 "Siliceous alpine and boreal grasslands").

With a specific example based on the subalpine habitat sub-type 6230*-C, we could quantify the negative effects on the regional conservation status assessment on different indicators when a habitat interpretation is extended beyond its definition, thus highlighting the importance of an accurate habitat interpretation (Biondi et al., 2012; Evans, 2010; Rodwell et al., 2018). We observed a different pattern among indicators and plant communities, suggesting that indicators' sensitivity can change according to habitat ecology. Therefore, it is essential to use more than a single indicator for evaluating the habitat conservation status and to consider more than just floristic indicators, especially for other habitat groups, such as forest habitats, where age structure and dead wood are very important (e.g., Cantarello and Newton, 2008; Kovač et al., 2020; Tsiripidis et al., 2018). A comprehensive monitoring campaign should include multiple surveys within an area to ensure an accurate assessment of the regional habitat conservation status. This is necessary to avoid misinterpretations caused by local variations within the same plant community. For instance, while *Nardus* may be absent in a single survey, it may be present in subsequent surveys of the same area, thus providing a more complete picture of the plant community.

The overall regional assessment of the habitat conservation status considers simultaneously considers range and area, structure and functions necessary for its long-term maintenance, and future prospects of survival (EC, 2023). Our procedure did not consider all the parameters needed for the conservation status assessment as required by the HD. However, compared to the habitat range and area, directly linked to the available suitable area, the structure, functions, and future prospects parameters might be more affected by any extension of the habitat interpretation, being based on species composition (Kirchmeir et al., 2013; Maciejewski et al., 2016), which can ultimately result in a negative assessment of the overall habitat conservation status at regional scale. Therefore, although extreme or misleading identification of the habitat can be avoided using more detailed habitat maps (e.g., Carli et al., 2020; Dalle Fratte et al., 2019; Mücher et al., 2009), this procedure might be helpful for policymakers and N2K site managers in identifying areas of priority monitoring.

Although indices to quantify the habitat structure and functions are much more advantageous (Kontula and Raunio, 2009), choosing objective thresholds of conservation status is challenging. One option could be to set reference sites representing different levels of conservation status (see Kovač et al., 2016). However, considering the ecological variability of habitats, many reference sites may be necessary to find applicable thresholds. A reference set of relevés of a specific habitat type or sub-type represent the ground for developing standardized tools and identifying accurate reference values for monitoring habitat conservation status at regional scale (Angelini et al., 2018; Delbosc et al., 2021). The evaluation of structure, functions and future prospects (including typical species) can be estimated quantitatively (Angiolini et al., 2021; Dalle Fratte et al., 2022; Kovač and Grošelj, 2018; Tsiripidis et al., 2018); however, their assignment to different classes of conservation status is still based on country-specific threshold values often defined by experts (Delbosc et al., 2021; Ellmauer, 2005; Søgaard et al., 2007; Tsiripidis et al., 2018; T'jollyn et al., 2009). A critical issue for developing robust and replicable conservation status assessment is thus the implementation of quantitative methods that avoid expert-based evaluations (Carignan and Villard, 2002; Kovač et al., 2016; Lengyel et al., 2008). Here, we have given an example of the calculation and application of standardized FRVs using percentiles thresholds (Bijlsma et al., 2019; Maciejewski et al., 2016). The approach described here could be used for other habitat groups and elsewhere in Europe when similar assessment methodologies are needed (e.g., for Emerald sites under the Berne Convention in non-EU countries).

Our findings highlighted that a remarkable portion of the habitat 6230* area is currently highly threatened by inadequate management (Kurtogullari et al., 2020). Smaller polygons at lower elevations are those experiencing a high rate of woody encroachment, which is one of the main threats at the European scale (Galvánek and Janák, 2008). Habitat 6230* in the lowlands deserves special attention due to the faster abandonment of traditional grazing activities and land-use intensification (Leuschner and Ellenberg, 2017), often resulting in high risk of eutrophication in the proximity of more intensive agricultural activities (Kurtogullari et al., 2020; Galvánek and Janák, 2008). According to our data, in the central southern Alps, a high number of the habitat 6230* polygons are currently located in the subalpine belt, and thus, restoration actions should be more focused on low-elevation pastures (Korzeniak, 2016; Kurtogullari et al., 2020). Despite this, MS implemented several conservation measures for all the habitat 6230* sub-types (Galvánek and Janák, 2008), which success might rely, in any case, on the correct habitat interpretation and mapping.

5. Conclusions

In this study, we evaluated the spatial distribution of the habitat 6230* within the N2K network of the Lombardy region (northern Italy, central southern Alps) concerning the main features essential for its definition: geological substrates, elevation and species richness. We found that the habitat 6230* interpretation also included plant communities on carbonate substrates and in the alpine belt, which identify plant communities at the extremes of its distribution. Focusing on the subalpine habitat sub-type (6230*-C), we could observe that plant communities at the extremes have a lower species richness, dominance and frequency of typical species. Therefore, their inclusion in habitat 6230* decreased its regional conservation status.

Our results suggest that *Nardus* grasslands at the extremes or beyond habitat definition should no longer refer to habitat 6230*. Otherwise, their monitoring would require specific thresholds case by case to fall inside FV conservation status. However, this way of proceeding would complicate things considerably, considering that habitat 6230* is widespread throughout the EU, and had troubled interpretative events.

Moreover, these semi-natural grasslands are crucial for both biodiversity conservation and high-quality dairy or livestock production. It is thus essential to identify projects and areas that can support successful restoration measures to reach FV conservation status, combined with sustainable agricultural land use, i.e., which safeguards both biodiversity and high-quality food products. A crucial step to achieve this objective would be identifying unique thresholds and robust indicators for monitoring the conservation status and developing incentives linked to good practices (e.g., result-based payments).

Although we considered the species-rich *Nardus* grasslands (habitat 6230*) as a case study, this procedure could fit other habitats for which identification took place with a broad interpretation or at least little considering the consequences on the regional conservation status assessments.

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CRediT authorship contribution statement

Michele Dalle Fratte: Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Bruno E.L. Cerabolini:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Andreis, C., Rodondi, G., 1982. I pascoli delle Alpi Orobie Orientali note vegetazionali per un catasto. Atti Conv. Attività silvo-pastorali ed aree protette (Corteno Golgi (Bs) 26–27 giugno 1982). Collana Di Storia Camuna, Studi e Testi 4, 85–107.

Angelini, P., Chiarucci, A., Nascimbene, J., Cerabolini, B.E.L., Fratte, M.D., Casella, L., 2018. Plant assemblages and conservation status of habitats of Community interest (Directive 92/43/EEC): Definitions and concepts. Ecol. Quest. 29 (3), 87–97. https://doi.org/10.12775/EQ.2018.025.

Angiolini, C., Foggi, B., Sarmati, S., Gabellini, A., Gennai, M., Castagnini, P., Mugnai, M., Viciani, D., Fanfarillo, E., Maccherini, S., 2021. Assessing the conservation status of EU forest habitats: The case of Quercus suber woodlands. For. Ecol. Manage. 496 https://doi.org/10.1016/j.foreco.2021.119432.

Armstrong, R.H., Grant, S.A., Common, T.G., Beattie, M.M., 1997. Controlled grazing studies on Nardus grassland: effects of between-tussock sward height and species of grazer on diet selection and intake. Grass Forage Sci. 52, 219–231. https://doi.org/10.2307/2404685.

Bartolucci, F., Peruzzi, L., Galasso, G., Albano, A., Alessandrini, A., Ardenghi, N.M.G., Astuti, G., Bacchetta, G., Ballelli, S., Banfi, E., Barberis, G., Bernardo, L., Bouvet, D., Bovio, M., Cecchi, L., Di Pietro, R., Domina, G., Fascetti, S., Fenu, G., Conti, F., 2018. An updated checklist of the vascular flora native to Italy. Plant Biosyst. 152 (2), 179–303. https://doi.org/10.1080/11263504.2017.1419996.

Bensettiti, Farid., Lepeltier, S., Galey, B.-P., 2005. Connaissance et gestion des habitats et des espèces d'intérêt communautaire. Tome 4. Habitats agropastoraux. Volume 1. «Cahiers d'habitats» Natura 2000. La Documentation française.

Bijlsma, R.J., Agrillo, E., Attorre, F., Boitani, L., Brunner, A., Evans, P., Foppen, R., Gubbay, S., Janssen, J.A.M., Van Kleunen, A., Langhout, W., Noordhuis, R., Pacifici, M., Ramírez, I., Rondinini, C., Van Roomen, M., Siepel, H., Winter, H.V., 2019. Defining and applying the concept of Favourable Reference Values for species and habitats under the EU Birds and Habitats Directives. Tech. Rep. www.wur.eu/environmental-research.

Biondi, E., Burrascano, S., Casavecchia, S., Copiz, R., Del Vico, E., Galdenzi, D., Gigante, D., Lasen, C., Spampinato, G., Venanzoni, R., Zivkovic, L., Blasi, C., 2012. Diagnosis and syntaxonomic interpretation of Annex I Habitats (Dir. 92/43/EEC) in Italy at the alliance level. Plant Sociol. 49 (1), 5–37. https://doi.org/10.7338/pls2012491/01.

Biondi, E., Blasi, C., Burrascano, S., Casavecchia, S., Copiz, R., Del Vico, E., Galdenzi, D., Gigante, D., Lasen, C., Spampinato, G., Venanzoni, R., Zivkovic Altri autori, L., Abdelahad, N., Aleffi, M., Allegrezza, M., Alongi, G., Andreis, C., Assini, S., Bacchetta, G., … Viciani, D. (2010). Manuale Italiano di interpretazione degli habitat della Direttiva 92/43/CEE. http://vnr.unipg.it/habitat/.

Bonari, G., Dalle Fratte, M., Lonati, M., Caccianiga, M., Lasen, C., Armiraglio, S., Barcella, M., Buffa, G., Cerabolini, B.E.L., Mainetti, A., Miserere, L., Oriolo, G., Selvaggi, A., 2023. Habitats Directive in northern Italy: a series of proposals for habitat definition improvement. Plant Sociol. 60 (1), 67–89. https://doi.org/10.3897/pls2023601/06.

Brusa, G., Cerabolini, B.E.L., Dalle Fratte, M., De Molli, C., 2017a. Protocollo operativo per il monitoraggio regionale degli habitat di interesse comunitario in Lombardia. Versione 1, 1.

Brusa, G., Dalle Fratte, M., Zanzottera, M., Cerabolini, B.E.L., 2017b. Come implementare la conoscenza floristico-vegetazionale in Lombardia? La banca dati degli habitat di interesse comunitario (Direttiva 92/43/CEE). Mus. Civ. Sc. Nat. Brescia 41, 45–66.

Caccianiga, M., Armiraglio, S., Andreis, C., 2000. Le formazioni con Carex curvula e i microarbusteti a Loiseleuria procumbens del versante meridionale delle Alpi Orobie. Fitosociologia 37 (1), 21–38.

Caccianiga, M., Andreis, C., Armiraglio, S., Leonelli, G., Pelfini, M., Sala, D., 2008. Climate continentality and treeline species distribution in the Alps. Plant Biosyst. 142 (1), 66–78. https://doi.org/10.1080/11263500701872416.

Cantarello, E., Newton, A.C., 2008. Identifying cost-effective indicators to assess the conservation status of forested habitats in Natura 2000 sites. For. Ecol. Manage. 256 (4), 815–826. https://doi.org/10.1016/j.foreco.2008.05.031.

Carignan, V., Villard, M.-A., 2002. Selecting Indicator Species to Monitor Ecological Integrity: A Review. Environ. Monit. Assess. 78, 45–61. https://doi.org/10.1023/A:1016136723584.

Carli, E., D'Alessandro, E., Di Marzio, P., Giancola, C., Paura, B., Salerno, G., Blasi, C., 2016. Monitoring natura 2000 habitats: Habitat 92A0 in central Italy as an example. Biogeographia 31 (1), 7–25. https://doi.org/10.21426/B631132735.

Carli, E., Massimi, M., Angelini, P., Casella, L., Attorre, F., Agrillo, E., 2020. How to improve the distribution maps of habitat types at national scale. Rendiconti Lincei 31 (3), 881–888. https://doi.org/10.1007/s12210-020-00917-7.

Carnino, N., 2009. État de conservation des habitats d'intérêt communautaire à l'échelle du site - Guide d'application de la méthode d'évaluation des habitats forestiers.

Carroll, J., Caporn, S., Johnson, D., Lee, J., 2003. The interactions between plant growth, vegetation structure and soil processes in semi-natural acidic and calcareous grasslands receiving long-term inputs of simulated pollutant nitrogen deposition. Environ. Pollut. 121, 363–376. https://doi.org/10.1016/S0269-7491(02)00241-5.

Cerabolini, B.E.L., Brusa, G., Ceriani, R.M., de Andreis, R., Luzzaro, A., Pierce, S., 2010. Can CSR classification be generally applied outside Britain? Plant Ecol. 210 (2), 253–261. https://doi.org/10.1007/S11258-010-9753-6.

Dalle Fratte, M., Brusa, G., Cerabolini, B.E.L., 2019. A low-cost and repeatable procedure for modelling the regional distribution of Natura 2000 terrestrial habitats. J. Maps 15 (2), 79–88. https://doi.org/10.1080/17445647.2018.1546625.

Dalle Fratte, M., Pierce, S., Zanzottera, M., Cerabolini, B.E.L., 2021. The association of leaf sulfur content with the leaf economics spectrum and plant adaptive strategies. Funct. Plant Biol. 48 (9), 924–935. https://doi.org/10.1071/FP20396.

Dalle Fratte, M., Caccianiga, M., Ricotta, C., Cerabolini, B.E.L., 2022. Identifying typical and early warning species by the combination of functional-based diagnostic species and dark diversity. Biodivers. Conserv. https://doi.org/10.1007/s10531-022-02427-4.

Del Vecchio, S., Slaviero, A., Fantinato, E., Buffa, G., 2016. The use of plant community attributes to detect habitat quality in coastal environments. AoB Plants 8. https://doi.org/10.1093/aobpla/plw040.

Delarze, R., Gonseth, Y., Eggenberg, S., Vust, M., 2015. Lebensräume Der Schweiz.

Delbosc, P., Lagrange, I., Rozo, C., Bensettiti, F., Bouzillé, J.B., Evans, D., Lalanne, A., Rapinel, S., Bioret, F., 2021. Assessing the conservation status of coastal habitats under Article 17 of the EU Habitats Directive. In: Biological Conservation, Vol. 254. Elsevier Ltd. https://doi.org/10.1016/j.biocon.2020.108935

Devillers, P., Devillers-Terschuren, J., Ledant, J.P., 1991. CORINE Biotopes Manual. Habitats of the European Community. Data specifications, Part 2. Commission of the European Communities, Directorate General Environment. Nuclear Safety and Civil Protection, Luxembourg, p. 300 pp..

Dinno, A., 2017. dunn.test: Dunn's Test of Multiple Comparisons Using Rank Sums. R package version 1.3.5.

Duprè, C., Stevens, C.J., Ranke, T., Bleeker, A., Peppler-Lisbach, C., Gowing, D.J.G., Dise, N.B., Dorland, E., Bobbink, R., Diekmann, M., 2010. Changes in species richness and composition in European acidic grasslands over the past 70 years: The contribution of cumulative atmospheric nitrogen deposition. Glob. Chang. Biol. 16 (1), 344–357. https://doi.org/10.1111/J.1365-2486.2009.01982.X.

EC, 2013. Interpretation manual of European Union habitats. EUR28. http://ec.europa.eu/environment/nature/legislation/habitatsdirective/docs/Int_Manual_EU28.pdf.

EC, 2023. Reporting under Article 17 of the Habitats Directive: Guidelines on concepts and definitions – Article 17 of Directive 92/43/EEC, Reporting period 2019-2024. https://cdr.eionet.europa.eu/help/habitats_art17/Reporting2025/Final%20Guidelines%20Art.%2017_2019-2024.pdf/.

EEA, 2021a. Biogeographical assessments of conservation status of species and habitats under Article 17 of the Habitats Directive. European Environmental Agency - European Topic Centre on Biological Diversity. https://nature-art17.eionet.europa.eu/article17/.

EEA, 2021b. EUNIS habitat type hierarchical view (marine version 2022 & terrestrial version 2021). https://eunis.eea.europa.eu/habitats-code-browser-revised.jsp.

Ellmauer, T., 1993. Calluno-Ulicetea. In: Grabherr, G., Ellmauer, T. (Eds.), Die Pflanzengesellschaften Österreichs. Teil i. Anthropogene Vegetation. Gustav Fischer Verlag, pp. 402–419.

Ellmauer, T., 2005. Entwicklung von kriterien, indikatoren und schwellenwerten zur beurteilung des erhaltungszustandes der Natura 2000-Schutzgüter. Band 3: lebensraumtypen des anhangs I der Fauna-Flora-Habitat-Richtlinie.

Evans, D., 2006. The habitats of the European Union Habitats Directive. *Source: Biology and Environment*. Proc. R. Ir. Acad. 106B (3), 167–173. http://www.jstor.orgURL: http://www.jstor.org/stable/20728591http://www.jstor.org/stable/20728591?seq=1&cid=pdf-reference#references_tab_contents.

Evans, D., 2010. Interpreting the habitats of Annex I: Past, present and future. Acta Botanica Gallica 157 (4), 677–686. https://doi.org/10.1080/12538078.2010.10516241.

Fischer, M., Wipf, S., 2002. Effect of low-intensity grazing on the species-rich vegetation of traditionally mown subalpine meadows. Biol. Conserv. 104 (1), 1–11. https://doi.org/10.1016/S0006-3207(01)00149-5.

Fremstad, E., 2002. Natura 2000 i Norge. - NTNU Vitenskapsmus. Rapp. Bot. Ser. 5, 1–38.

Galvánek, D., Janák, M., 2008. Management of Natura 2000 habitats: 6230* Species-rich Nardus grasslands. European Commission.

Gennai, M., Foggi, B., Viciani, D., Carbognani, M., Tomaselli, M., 2014. The Nardus-rich communities in the northern Apennines (N-Italy): A phytosociological, ecological and phytogeographical study. Phytocoenologia 44 (1–2), 55–80. https://doi.org/10.1127/0340-269X/2014/0044-0574.

Gerdol, R., Piccoli, F., 1980. Inquadramento fitosociologico e valutazione ecologica delle formazioni prative montane del Monte Baldo. Arch. Bot. Biogeogr. Ital. 56 (3–4), 101–133.

Giacomini, V., Pirola, A., Vikus, E., 1962. I pascoli dell'alta Valle di S. Giacomo (Spluga). Flora et Vegetatio Italica. Memoria 4. Gianasso editore.

Giacomini, V., Pignatti, S., 1955. Flora e vegetazione dell'Alta Valle del Braulio, con speciale riferimento ai pascoli di altitudine. Mem. Soc. Ital. Sc. Nat. Milano 11 (2–3), 1–194.

Grabherr, G., 1993. Caricetea-curvulae. In: Grabherr, G., Mucina, L. (Eds.), Die Pflanzengesellschaften Österreichs. Teil II - Natürliche Waldfreie Vegetation. Gustav Fischer Verlag, pp. 343–372.

Grime, J.P., 2006. Plant Strategies, Vegetation Processes, and Ecosystem Properties, 2nd ed. John Wiley & Sons.

Janssen, J.A.M., Rodwell, J.S., García Criado, M., Gubbay, S., Haynes, T., Nieto, A., Sanders, N., Calix, M., 2016. European red list of habitats: Part 2. Terrestrial and Freshwater Habitats. https://doi.org/10.2779/091372 Highlight.

Kirchmeir, H., Köstl, T., Getzner, M., Zak, D., 2013. Transnational joint strategy and tools fort he better management and implementation of Natura 2000 sites.

Kontula, T., Raunio, A., 2009. New method and criteria for national assessments of threatened habitat types. Biodivers. Conserv. 18 (14), 3861–3876. https://doi.org/10.1007/s10531-009-9684-5.

Korzeniak, J., 2016. Mountain Nardus stricta grasslands as a relic of past farming – the effects of grazing abandonment in relation to elevation and spatial scale. Folia Geobot. 51 (2), 93–113. https://doi.org/10.1007/s12224-016-9246-z.

Kovač, M., Gasparini, P., Notarangelo, M., Rizzo, M., Cañellas, I., Fernández-de-Uña, L., Alberdi, I., 2020. Towards a set of national forest inventory indicators to be used for assessing the conservation status of the habitats directive forest habitat types. J. Nat. Conserv. 53, 125747 https://doi.org/10.1016/j.jnc.2019.125747.

Kovač, M., Grošelj, P., 2018. Toward objective assessment of the conservation status of (the Natura 2000) forest habitat types: A comparison of a qualitative and a quantitative modeling approach. Ecol. Ind. 89, 281–289. https://doi.org/10.1016/j.ecolind.2018.02.001.

Kovač, M., Kutnar, L., Hladnik, D., 2016. Assessing biodiversity and conservation status of the Natura 2000 forest habitat types: Tools for designated forestlands stewardship. For. Ecol. Manage. 359, 256–267. https://doi.org/10.1016/j.foreco.2015.10.011.

Kurtogullari, Y., Rieder, N.S., Arlettaz, R., Humbert, J.Y., 2020. Conservation and restoration of Nardus grasslands in the Swiss northern Alps. Appl. Veg. Sci. 23 (1), 26–38. https://doi.org/10.1111/AVSC.12462.

Landolt, E., Bäumler, B., Erhardt, A., Hegg, O., Klötzli, F., Lämmler, W., Nobis, M., Rudmann-Maurer, K., Schweingruber, F., Theurillat, J.-P., Urmi, E., Vust, M., Wohlgemuth, T., 2010. Flora Indicativa. Haupt Verlag.

Lengyel, S., Déri, E., Varga, Z., Horváth, R., Tóthmérész, B., Henry, P.Y., Kobler, A., Kutnar, L., Babij, V., Seliškar, A., Christia, C., Papastergiadou, E., Gruber, B., Henle, K., 2008. Habitat monitoring in Europe: A description of current practices. Biodivers. Conserv. 17 (14), 3327–3339. https://doi.org/10.1007/s10531-008-9395-3.

Leuschner, C., Ellenberg, H., 2017. Ecology of central European non-forest vegetation: coastal to alpine, natural to man-made habitats. In: Vegetation Ecology of Central Europe, Vol. II. Springer International Publishing Switzerland, p. (p. 1093).. https://doi.org/10.1007/978-3-319-43048-5.

Lüth, C., Tasser, E., Niedrist, G., Dalla Via, J., Tappeiner, U., 2011. Classification of the Sieversio montanae-Nardetum strictae in a cross-section of the Eastern Alps. Plant Ecol. 212 (1), 105–126. https://doi.org/10.1007/s11258-010-9807-9.

MacDonald, D., Crabtree, J.R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., Gutierrez Lazpita, J., Gibon, A., 2000. Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. J. Environ. Manage. 59 (1), 47–69. https://doi.org/10.1006/jema.1999.0335.

Maciejewski, L., Lepareur, F., Viry, D., Bensettiti, F., Puissauve, R., Touroult, J., 2016. Etat de conservation des habitats propositions de définitions et de concepts pour l'évaluation à l'échelle d'un site Natura 2000. Revue D'ecologie (terre Et Vie) 71 (1), 3–20.

Maurer, K., Weyand, A., Fischer, M., Stöcklin, J., 2006. Old cultural traditions, in addition to land use and topography, are shaping plant diversity of grasslands in the Alps. Biol. Conserv. 130 (3), 438–446. https://doi.org/10.1016/j.biocon.2006.01.005.

Mücher, C.A., Hennekens, S.M., Bunce, R.G.H., Schamineée, J.H.J., Schaepman, M.E., 2009. Modelling the spatial distribution of Natura 2000 terrestrial habitats across Europe. Landsc. Urban Plan. 92, 148–159. https://doi.org/10.1016/j.landurbplan.2009.04.003.

Mucina, L., Bültmann, H., Dierßen, K., Theurillat, J.P., Raus, T., Čarni, A., Tichý, L., 2016. Vegetation of Europe: hierarchical floristic classification system of vascular plant, bryophyte, lichen, and algal communities. Appl. Veg. Sci. 19, 3–264. https://doi.org/10.1111/avsc.12257.

Newton, A.C., Walls, R.M., Golicher, D., Keith, S.A., Diaz, A., Bullock, J.M., 2012. Structure, composition and dynamics of a calcareous grassland metacommunity over a 70-year interval. J. Ecol. 100 (1), 196–209. https://doi.org/10.1111/j.1365-2745.2011.01923.x.

Orsenigo, S., Fenu, G., Gargano, D., Montagnani, C., Abeli, T., Alessandrini, A., Bacchetta, G., Bartolucci, F., Carta, A., Castello, M., Cogoni, D., Conti, F., Domina, G., Foggi, B., Gennai, M., Gigante, D., Iberite, M., Peruzzi, L., Pinna, M.S., Rossi, G., 2021. Red list of threatened vascular plants in Italy. Plant Biosyst. 155 (2), 310–335. https://doi.org/10.1080/11263504.2020.1739165.

Parolo, G., Abeli, T., Gusmeroli, F., Rossi, G., 2011. Large-scale heterogeneous cattle grazing affects plant diversity and forage value of Alpine species-rich Nardus pastures. Grass Forage Sci. 66 (4), 541–550. https://doi.org/10.1111/j.1365-2494.2011.00810.x.

Peppler-Lisbach, C., Stanik, N., Könitz, N., Rosenthal, G., 2020. Long-term vegetation changes in Nardus grasslands indicate eutrophication, recovery from acidification, and management change as the main drivers. Appl. Veg. Sci. 23 (4), 508–521. https://doi.org/10.1111/avsc.12513.

Pignatti, S., Guarino, R., La Rosa, M., 2017. Flora d'italia [Italian Flora] (2nd edition). Italy, Edagricole, Bologna, p. 1178.

Pittarello, M., Lonati, M., Gorlier, A., Probo, M., Lombardi, G., 2017. Species-rich Nardus stricta grasslands host a higher vascular plant diversity on calcareous than on siliceous bedrock. Plant Ecolog. Divers. 10 (4), 343–351. https://doi.org/10.1080/17550874.2017.1393703.

Prévosto, B., Kuiters, L., Bernhardt-Römermann, M., Dölle, M., Schmidt, W., Hoffmann, M., Van Uytvanck, J., Bohner, A., Kreiner, D., Stadler, J., Klotz, S., Brandl, R., 2011. Impacts of Land Abandonment on Vegetation: Successional Pathways in European Habitats. Folia Geobot. 46 (4), 303–325. https://doi.org/10.1007/s12224-010-9096-z.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rodwell, J.S., Evans, D., Schaminée, J.H.J., 2018. Phytosociological relationships in European Union policy-related habitat classifications. Rendiconti Lincei 29 (2), 237–249. https://doi.org/10.1007/s12210-018-0690-y.

Søgaard, B., Skov, F., Ejrnæs, R., Pihl, S., Reinholt Fredshavn, J., Erik Nielsen, K., Clausen, P., Laursen, K., Bregnballe, T., Madsen, J., Baatrup-Pedersen, A., Søndergaard, M., Lauridsen, T.L., Aude, E., Ny-gaard, B., Møller, P., Riis-Nielsen, T., Buttenschøn, R.M., 2007. Criteria for Favourable Conservation Status in Denmark. Natural Habitat Types and Species Covered by the EEC Habitats Directive and Birds Covered by the EEC Birds Directive. NERI Technical Report No. 647.

Stanová, V., Valachovič, M., 2022. Katalóg biotopov Slovenska. DAPHNE – Inštitút aplikovanej ekológie.

Stevanović, Z Dajić et al. 2008. "Long Term Grassland Vegetation Changes : Case Study Nature Park Stara Planina (Serbia)." Community Ecology 9: 23–31. doi:10.1556/ComEc.9.2008.S.5.

Tasser, E., Tappeiner, U., 2002. Impact of land use changes on mountain vegetation. Applied vegetation science 5 (2), 173–184. https://doi.org/10.1111/j.1654-109X.2002.tb00547.x.

T'jollyn, F., Bosch, H., Demolder, H., De Saeger, S., Leyssen, A., & Thomaes, A. (2009). Criteria voor de beoordeling van de lokale staat van instandhouding van de Natura 2000-habitattypen. Versie 2.0. INBO.R.2009.46.

Tsiripidis, I., Xystrakis, F., Kallimanis, A., Panitsa, M., Dimopoulos, P., 2018. A bottom–up approach for the conservation status assessment of structure and functions of habitat types. Rendiconti Lincei 29 (2), 267–282. https://doi.org/10.1007/s12210-018-0691-x.

Zanzottera, M., Dalle Fratte, M., Caccianiga, M., Pierce, S., Cerabolini, B.E.L., 2020. Community-level variation in plant functional traits and ecological strategies shapes habitat structure along succession gradients in alpine environment. Community Ecol. 21 (1), 55–65. https://doi.org/10.1007/s42974-020-00012-9.