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ORIGINAL ARTICLE

Habitat characteristics, ecology and biodiversity drivers of plant communities associated with *Cousinia edmondsonii*, an endemic and critically endangered species in NE Iran

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Abstract

Mountains hold high species diversity and endemism because of topographic diversity and isolation. Many mountainous regions are being affected by climate changes. Furthermore, mountain soils can affect plant communities by altering species components and community structure. The sub-alpine areas of western Khorassan-Kopet Dagh Mountains in the Irano-Turanian region have received little attention. We aim to provide new information on vegetation, ecological characteristics, and biodiversity drivers of plant communities associated with *Cousinia edmondsonii*, a very narrow endemic and critically endangered plant in NE Iran. We sampled 35 vegetation plots by stratified-random sampling in this area. Modified TWINSPAN and DCA analyses were used to classify plant communities. We used CCA analyses to assess vegetation-environment relationships and Hill numbers to evaluate diversity in plant communities. In all, 127 species were recorded, belonging to 83 genera and 29 families. The hemicryptophytes and Irano-Turanian elements were the dominant life-form and chorotype, respectively. Endemic and sub-endemic species comprised 41 species in the study area. Five plant communities types are identified in the study area based on the diagnostic and dominant species. *Stipa lessingiana-Acantholimon erinaceum* and *Muscari neglectum-Juniperus sabina* communities are dominated by thorny cushion and dwarf shrubby species, respectively. The communities dominated by *C. edmondsonii*, i.e., *Gypsophila aretioides-Cousinia edmondsonii*, *Alyssum lanigerum-Cousinia edmondsonii*, and *Thymus kotschyanus-Cousinia edmondsonii*, exhibited higher species diversity than the other communities. Based on CCA, the composition of plant communities was significantly correlated with seven topographic and environmental factors. The results showed that *C. edmondsonii*, its habitats, and vegetation types in the higher mountains of western Khorassan-Kopet Dagh deserve special conservation attention.

Keywords Aladagh Mountains · Conservation · Environmental factors · Floristic analysis · Irano-Turanian · Vegetation

Introduction

Mountains constitute more than 50% of global biodiversity hotspots and hold high species diversity and endemism (Munson & Sher, 2015; Noroozi et al., 2018). Many mountainous regions are being affected by recent changes in climate such that higher temperatures or lower rainfall affect the vegetation in both quantity and quality. Furthermore, mountain soils are highly dynamic and may react sensitively to environmental changes; soils can affect plant communities by altering species component and community structure (Cowles et al., 2016). These factors can in particular affect endemic species in these regions and lead to species extinction because of their geographic isolation and limited geographic ranges (Grabherr et al., 1994). Therefore, these regions are considered as significant for biodiversity

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conservation at global, national, and local scales (Noroozi et al., 2019).

The Irano-Turanian Floristic Region consists of a vast territory in southwestern and central Asia in the Holarctic, connecting to the Mediterranean, Euro-Siberian, and Saharo-Sindian regions. The region has a high level of plant speciation and endemism, especially in genera including *Astragalus*, *Cousinia*, *Acantholimon*, *Acanthophyllum*, and *Allium* (Takhtajan, 1986; Zohary, 1973; Léonard, 1991; Noroozi 2020). Several biogeographic units have been distinguished within this region including the Khorassan-Kopet Dagh (KK) Floristic Province located in northeastern Iran and southern Turkmenistan. This area is mainly mountainous and is a transition zone connecting different provinces of the Irano-Turanian Region and the Hyrcanian montane forests of the Euro-Siberian Region. Different mountain ranges make up the KK Floristic Province that show high biodiversity and endemism (Memariani, 2020; Memariani et al., 2016a).

The Irano-Turanian genus *Cousinia* Cass. (Asteraceae), with about 664 accepted species (POWO, 2023), is the largest genus in the tribe Cardueae (Mehregan & Kadereit, 2009). It is unique in the degree of diversification and the restricted area of many species, mainly in southwestern and central Asia (Rechinger, 1986). Many *Cousinia* species have been geographically isolated in the high mountain interglacial refugia of the Irano-Turanian region, thereby fostering its allopatric speciation (Djamali et al., 2012). Pamir- Alay range in Middle Asia is the main center of *Cousinia* species diversity, with ca. 170 species, of which 130 are endemics (Knapp, 1987). The KK Floristic Province is considered the second important center of the diversification of *Cousinia*. There ara ca. 100 species, 70% of which are endemic to this area (Memariani & Joharchi, 2011; Memariani et al., 2016b; Zare et al., 2013). The Aladagh and Ghorkhod mountains located in the western part of KK Floristic Province include main sub-alpine areas with a high diversity of topography, floristics, and physiognomy of vegetation, as well as many endemics (Arjmandi et al., 2021; Memariani et al., 2016c). *Cousinia edmondsonii* Rech.f. is an endemic species described originally from the Ghorkhod Mount as an isolated species with unknown sectional placement (Rechinger, 1972). Mehregan and Assadi (2016) placed the species within the *Cousinia* section *Pseudactinia* Tscherneva which comprises five endemic species restricted to the KK and partly to the eastern Alborz Mountains. Memariani et al. (2016c) recorded several patches of rock and cliff vegetation dominated by *C. edmondsonii* restricted to the sub-alpine zone on the northern slopes of Ghorkhod Mount. Recently, the second location for this species has been recorded from the Barfandil summit in Aladagh Mountains (Arjmandi et al., 2021). *C. edmondsonii*, with pale green to silver leaves, a height of about 70 cm, and a canopy diameter of up to 100 cm, is similar to cushion plants in terms of life-form. It is a very narrow endemic species evaluated as critically endangered (CR) due to its limited extent of occurrence and area of occupancy (Memariani et al., 2016b).

In this paper, we present an ecological study of the structure and composition of sub-alpine vegetation in the Aladagh and Ghorkhod Mountains which are the only known habitats of the critically endangered species *Cousinia edmondsonii* in the world. The objectives of the study were (1) to provide floristic information on this area in terms of life-forms, chorotypes, and plant endemism; (2) to determine plant communities and species composition in the study area; (3) to identify environmental variables influencing plant community formation and vegetation structure; and (4) to compare biodiversity among the plant communities. This study is the first comprehensive assessment of the ecology and habitat characteristics of this area. The results can improve conservation and planning management for sub-alpine regions in northeastern Iran.

Materials and methods

Study area

The study area is located in the sub-alpine vegetation dominated by or associated with *Cousinia edmondsonii* in the western Aladagh (between 37°22′43″ and 37°23′01″ N latitude and 56°46′56″ and 56°47′18″ E longitude) and Ghorkhod mountains (between 37°26′14″ and 37°27′57″ N latitude and 56°27′24″ and 56°30′04″ E longitude). The area belongs to the western part of the KK Floristic Province (Fig. 1a, b). Geologically, the area belongs to the Kopet Dagh zone, mainly composed of Middle to Upper Jurassic age, sedimentary rocks including limestone, and marl of the Chaman-Bid and Mozduran formation (Memariani et al., 2016b). The area is located in Irano-Turanian xeric-continental bioclimatic zone of Khorassan-Kopet Dagh (Djamali et al., 2011), with highest precipitation from late autumn to early spring, with a summer drought. Based on the closest stations to the sampling sites, the mean annual precipitation and the mean annual temperature is 322 mm and 10.2 °C for Darkesh station (1200 m a.s.l.) in the north of western Aladagh, and 235 mm and 16.6 °C for Chaman-Bid station (1540 m a.s.l.) in the south of Ghorkhod Mount, respectively.

Floristic and vegetation sampling

We sampled 35 vegetation plots (5×5 m^2) in plant communities hosting the target species *Cousinia edmondsonii* on the sub-alpine slopes of the Aladagh (26 plots) and Ghorkhod mountains (9 plots). These two main habitats of the species

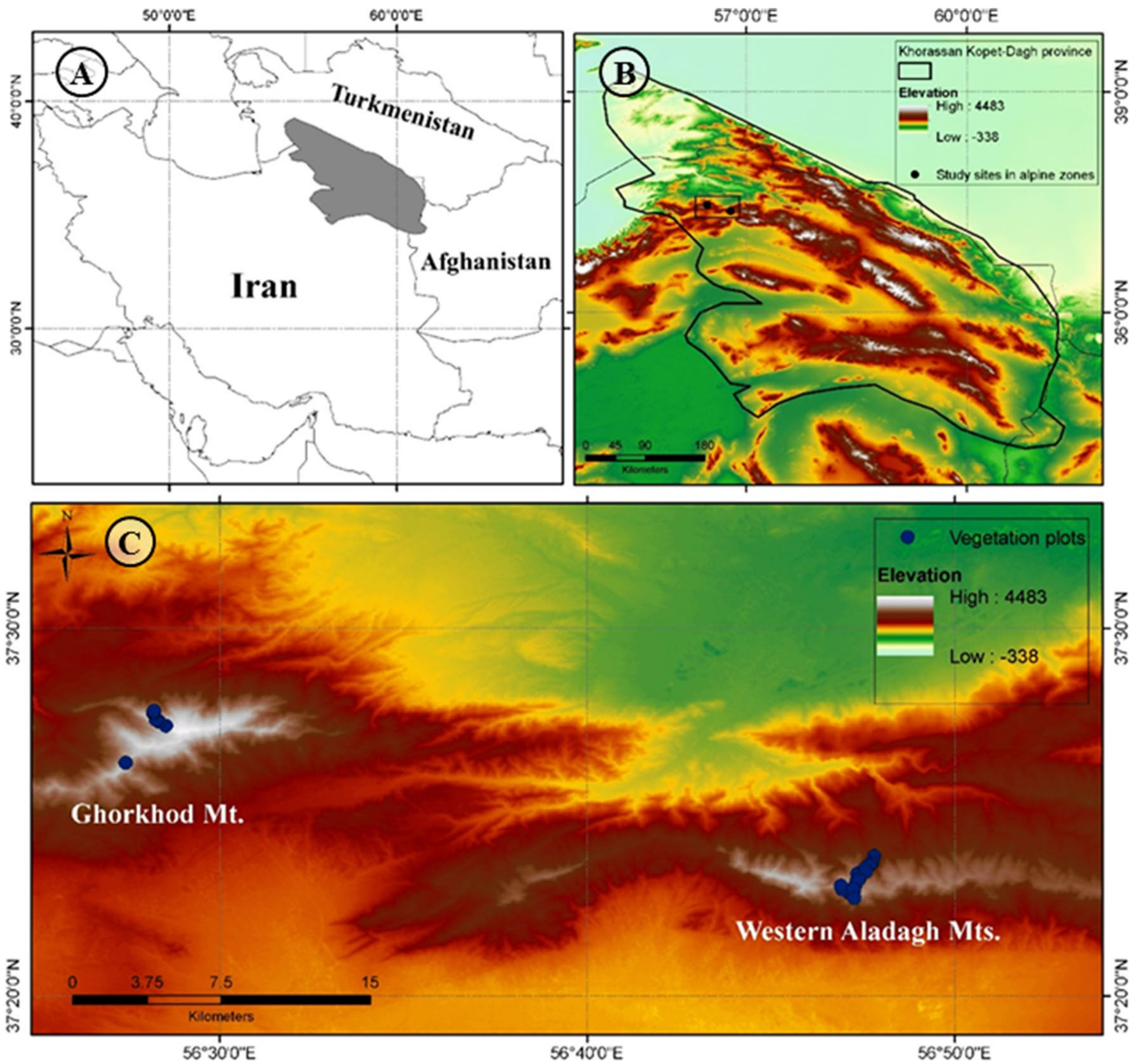

Fig. 1 Maps of the study area: **a**, Geographic position of the Khorassan-Kopet Dagh (KK) Floristic Province; **b**, Topographic map of the mountain systems in KK and position of the study areas in western part of the KK; **c**, Topographic map and the sampling sites in Ghorkhod and Aladagh Mountains. Prepared using ArcGIS 10.3 software (www.esri.com)

are located at a distance of 30 km from each other (Fig. 1c). We used stratified-random plots during spring–summer (late May- early July) of 2018–2019. In each plot, canopy cover was estimated visually as a percentage of ground area, and the Braun-Blanquet cover-abundance scale was obtained following the Zürich-Montpellier approach (Barkmann et al., 1964). The vegetation data were stored in the TURBOVEG (ver. 2.133c) database (Hennekens & Schaminée, 2001) for later analyses.

All vascular plant species in sample plots were recorded; their life-form and chorotype were determined using the relevant literature and floras (Rechinger 1963–2015; Assadi et al. 1988–2018; Memariani et al., 2016b, 2016c). Terminology of phytogeographic units (Irano-Turanian, Mediterranean, Euro-Siberian, and Sahara-Sindian) followed Léonard (1988, 1991), Akhani (1998), and Memariani et al. (2016a).

The description and classification of life-forms followed Raunkiaer (1934) and threat categories were obtained from Jalili and Jamzad (1999) and Memariani et al. (2016b). All specimens are deposited in FUMH (Herbarium of Ferdowsi University of Mashhad).

Environmental factors

Environmental factors such as soil characteristics and topography (slope aspect, degrees of slope) were recorded for each plot. Soil samples (~500 g) were collected from the center of each plot at a depth of 10–25 cm and taken to the laboratory. To avoid the variability in soil moisture measurements, we collected 35 soil samples separately from all vegetation plots during a single day. The following properties were measured: nitrogen, organic carbon, organic matter, soil texture, clay, silt, sand, phosphorus, potassium, pH, soil moisture, total neutralizing value (TNV) of the limestone (Rayburn, 2014), and soil electrical conductivity (EC). These factors are among the effective environmental factors in the separation of different vegetation types in Iran (Gholizadeh et al., 2020; Jafari et al., 2004; Naqinezhad et al., 2008). Soil texture was measured by hydrometric method (Gee & Bauder, 1986), total nitrogen by Kjeldahl method (Bremner & Mulvaney, 1982), organic carbon percentage by Walkley–Black procedure (Bahadori & Tofighi, 2016), soil phosphorus and potassium content by modified Kelowna extraction method (Qian et al., 1994). We calculated the soil moisture by comparing the wet and dry weight, and the soil pH by measuring saturated soil acidity (van Reeuwijk, 2002).

Data analysis

Classification and ordination techniques were used for vegetation analyses. The classification of the vegetation data was performed using modified TWINSPAN (Hill, 1979) with nine pseudo-species cut levels (0, 1, 2.5, 5, 12.5, 25, 50, 75, 100) to provide a better classification based on what is observed in nature. After sorting vegetation with modified TWINSPAN, diagnostic species were determined on the basis of the fidelity concept using the *phi* coefficient in JUICE ver. 7.0 (Tichý et al. 2002). The threshold *phi* value for the indicator species was set at 0.30, with a 5% significance level for Fisher's exact test (Chytrý et al., 2002; Kusbach et al., 2012). Detrended correspondence analysis (DCA) was also used to ordinate the plots in two-dimensional space. We used canonical correspondence analysis (CCA; Anderson & Willis, 2003) to assess vegetation-environment relationships (Leps & Smilauer, 1999). Collinear environmental variables with high variance inflation factors (VIF > 10) were eliminated from further analyses (Neter et al., 1996; Legendre and Legendre 2012). The significance of the CCA axes and species-environment correlations were assessed using permutation tests (999 permutations, $P < 0.05$). We used the Hill numbers to compare the diversity in plant communities. DCA and CCA analysis were performed in R 3.6.0, using the VEGAN package (Oksanen et al., 2012).

Conservation assessment

The previous distribution data (Memariani et al., 2016b) and the newly collected occurrence data for *Cousinia edmondsonii* in the study area was mapped in the GeoCAT tool (Bachman et al., 2011). We calculated the extent of occurrence (EOO) and area of occupancy (AOO) to re-evaluate the conservation status of the species based on the IUCN Red List categories and criteria (IUCN, 2019).

Results

Floristic diversity and phytogeography

In total, 127 species were recorded belonging to 83 genera and 29 families. Floristic analysis revealed that the richest families are Brassicaceae, Poaceae, and Asteraceae (Fig. S1). Hemicryptophytes were the dominant life-form in this region, followed by chamaephytes, cryptophytes (geophytes), and phanerophytes (Fig. S2). The dominant contributing chorotype were Irano-Turanian (IT) elements (72.2%), whereas bi-regional (12.8%), tri-regional (9.77%), and widespread species (3.76%) had smaller contributions, respectively (Fig. S3). Central Irano-Turanian (IT^{C}) and Irano-Turanian species endemic to the Khorassan-Kopet Dagh Floristic Province (IT^{KK}) were most common among IT elements (Fig. S4). Endemic and sub-endemic species comprised 14.2% (18 species) and 18.1% (23 species) of the overall flora in the study area, respectively.

Classification

Vegetation plots are classified at the four levels into five vegetation groups (Table 1; Fig. 2). In total, 70 diagnostic species are identified for all plots of the five groups. Table 2 shows a simplified frequency-fidelity synoptic table of five vegetation groups on the basis of 35 sampled plots with diagnostic species for each group. Five plant community types (CTs) are determined based on the diagnostic and dominant species, including CT1: *Stipa lessingiana-Acantholimon erinaceum*, CT2: *Muscari neglectum-Juniperus sabina*, CT3: *Gypsophila aretioides-Cousinia edmondsonii*, CT4: *Alyssum lanigerum-Cousinia edmondsonii*, and CT5: *Thymus kotschyanus-Cousinia edmondsonii*.

According to the dendrogram obtained from modified TWINSPAN (Fig. 2), the plots were divided into two main groups. Group 1 included two communities (CT1, CT2), whereas the other three communities (CT3, CT4, CT5) belonged to Group 2. *Thymus transcaspicus* (78.8%), with highest fidelity, was the first diagnostic species, followed by *Hypericum scabrum* (72.8%) and *Poa bulbosa* (70.4%) in the Group 1. The Group 2 was characterized by diagnostic species, including *Cousinia edmondsonii* (100.0, the highest fidelity), *Festuca valesiaca* (71.9), *Dianthus orientalis* (54.2), and *Erysimum ischnostylum* (50.7). *Stipa lessingiana* and *Muscari neglectum*, with highest fidelity (100%), were diagnostic species for the CT1 and CT2 in the Group 1. The CT1 is located at elevations of

Table 1 Plant communities and plot numbers in each community in the study area

Plots in each community*	Community types (CT)	Community groups
CT1 (P22- P23- P24- P25)	*Stipa lessingiana- Acantholimon erinaceum*	*Thymus transcaspicus* communities (associated with *Cousinia edmondsonii*)
CT2 (P13- P14- P15- P16- P17- P18- P19- P20- P21)	*Muscari neglectum- Juniperus sabina*	
CT3 (P3- P4- P8- P9- P26)	*Gypsophila aretoides- Cousinia edmondsonii*	*Cousinia edmondsonii communities*
CT4 (P1- P5- P6- P7- P10- P11- P12)	*Alyssum lanigerum- Cousinia edmondsonii*	
CT5 (P2- P27- P28- P29- P30- P31- P32- P33- P34—P35)	*Thymus kotschyanus- Cousinia edmondsonii*	

*Plots number 1–9 and 10–35 are sampled from Ghorkhod and Aladagh sites, respectively

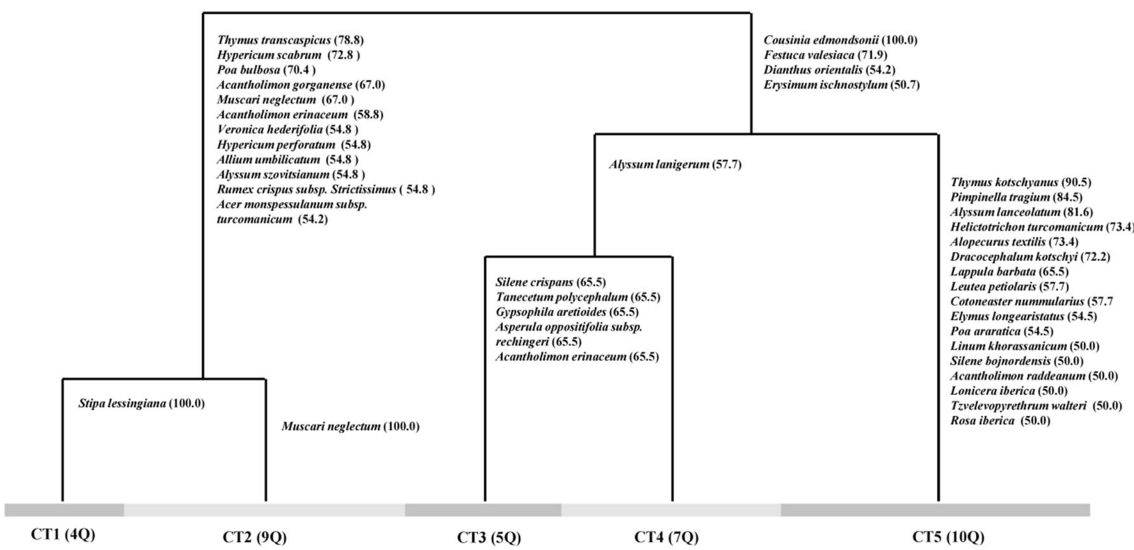

Fig. 2 The dendrogram of TWINSPAN classification of the five plant communities (CT1-CT5), together with their indicator species resulted from classification of the 35 sample plots (Q)

2150–2250 m a.s.l. and *Acantholimon erinaceum* is the dominant species in this community, whereas the CT2, with dominance of *Juniperus sabina*, occurs at elevations of 2000–2150 m a.s.l. Diagnostic species with the highest fidelity were *Silene crispans* (65.5%) and *Thymus kotschyanus* (90.5%) for the communities CT3 and CT5 in the Group 2, respectively. The communities CT3, CT4, and CT5 are located at elevations of 2250–2380 m a.s.l. and the dominant species in these communities is *Cousinia edmondsonii*. Based on sampled plots (Table 1), the communities CT1 and CT2 occur only at Aladagh site; however, the other communities are distributed in both Aladagh and Ghorkhod sites. Figure 3 shows some community types with their representative dominant or diagnostic species in the study area.

Ordination

DCA analysis on the standardized matrix of plots showed that the five plant communities obtained from modified TWINSPAN analysis are well separated along the first four DCA axes, with eigenvalues of 0.56, 0.43, 0.27, and 0.23, respectively (Fig. 4). The high values of the first two axes of DCA indicate that they explain a high proportion of the variance of vegetation changes. Furthermore, the length of the first axis of the unit (3.97 SD) and the length of the second axis of the unit (3.3 SD) reflected the high beta diversity in this region (Table S1). Based on the DCA graph, communities CT1 and CT2 were distributed at the positive end of the first axis of DCA, while the other three communities occupied the negative end. The DCA graph confirmed the patterns expected from the modified TWINSPAN classification.

Table 2 Fidelity table of five communities obtained by TWINSPAN classification. Diagnostic species for each groups are shaded

Community number	CT1	CT2	CT3	CT4	CT5
Number of species in the community	33	32	29	20	30
Elevation	2100–2250 m	2000–2150 m	2250–2380 m	2250–2380 m	2250–2380 m
Group No.	1	2	3	4	5
No. of relevés	4	9	5	8	9
Stipa lessingiana	78.2	–	–	–	–
Allium umbilicatum	64.7	–	–	–	–
Poa densa	57.7	–	–	–	–
Acantholimon erinaceum	50.4	–	–	–	–
Muscari neglectum	–	86.1	–	–	–
Hypericum scabrum	–	78.8	–	–	–
Acer monspessulanum subsp. *turcomanicum*	–	78.5	–	–	–
Hypericum perforatum	–	78.4	–	–	–
Alyssum szovitsianum	–	70.7	–	–	–
Rumex crispus subsp. *strictissimus*	–	70.7	–	–	–
Prangos ferulacea	–	70.7	–	–	–
Melica persica	–	70.7	–	–	–
Rosa beggeriana	–	70.7	–	–	–
Juniperus sabina	–	66.8	–	–	–
Dactylis glomerata subsp. *glomerata*	–	62.5	–	–	–
Lomelosia micrantha	–	62.5	–	–	–
Cotoneaster nummularioides	–	62.5	–	–	–
Elwendia cylindrica	–	62.5	–	–	–
Asperula glomerata subsp. *turcomanica*	–	62.1	–	–	–
Lonicera iberica	–	62.1	–	–	–
Thymus transcaspicus	–	53.9	–	–	–
Allium grande	–	53.5	–	–	–
Isatis gaubae	–	53.5	–	–	–
Acantholimon gorganense	–	38.8	–	–	–
Teucrium polium	–	36.8	–	–	–
Veronica hederifolia	–	32.6	–	–	–
Noccaea perfoliata	–	–	65.5	–	–
Stipa caucasica	–	–	64.6	–	–
Alyssum inflatum	–	–	59.0	–	–
Allium lenkoranicum	–	–	59.0	–	–
Alyssum lanigerum	–	–	51.1	–	–
Allium rubellum	–	–	–	56.9	–
Silene crispans	–	–	–	56.9	–
Campanula oreodoxa	–	–	–	56.9	–
Onobrychis cornuta	–	–	–	37.8	–
Alopecurus textilis	–	–	–	–	85.8
Thymus kotschyanus	–	–	–	–	81.3
Alyssum lanceolatum	–	–	–	–	73.4
Pimpinella tragium subsp. *pseudotragium*	–	–	–	–	72.9
Leutea petiolaris	–	–	–	–	70.7
Poa araratica	–	–	–	–	69.6
Helictotrichon turcomanicum	–	–	–	–	65.2
Acantholimon raddeanum	–	–	–	–	62.5
Linum khorassanicum	–	–	–	–	62.5
Tzvelevopyrethrum walteri	–	–	–	–	62.5
Asperula oppositifolia subsp. *rechingeri*	–	–	–	–	60.4

Table 2 (continued)

Community number	CT1	CT2	CT3	CT4	CT5
Dracocephalum lindbergii	–	–	–	–	57.7
Gypsophila pulvinaris	–	–	–	–	56.4
Cotoneaster nummularius	–	–	–	–	55.2
Carex hallerana	–	–	–	–	53.5
Hypericum elongatum	–	–	–	–	53.5
Astragalus jolderensis	–	–	–	–	53.5
Artemisia chamaemelifolia	–	–	–	–	53.5
Lappula barbata	–	–	–	–	50.5
Elymus longearistatus	–	–	–	–	49.8
Koeleria macrantha	–	–	–	–	45.5
Poa bulbosa	48.8	37.7	–	–	–
Festuca valesiaca	–	–	56.5	31.3	–
Cousinia edmondsonii	–	–	–	40.8	40.8
Fibigia suffruticosa	–	–	–	–	–
Stachys turcomanica	–	–	–	–	–
Polygonatum orientale	–	–	–	–	–
Rosa canina x R. iberica	–	–	–	–	–
Prunus divaricata	–	–	–	–	–
Galium verum	–	–	–	–	–
Fraxinus angustifolia	–	–	–	–	–
Verbascum sinuatum	–	–	–	–	–
Cerastium dichotomum	–	–	–	–	–
Jurinea sintenisii	–	–	–	–	–
Sabulina lineata	–	–	–	–	–
Astragalus kopetdaghi	–	–	–	–	–
Ephedra major	–	–	–	–	–
Saponaria bodeana	–	–	–	–	–
Colutea buhsei	–	–	–	–	–
Minuartia hamata	–	–	–	–	–
Dianthus orientalis subsp. *stenocalyx*	–	–	–	–	–
Tragopogon dubius	–	–	–	–	–
Bromus kopetdaghensis	–	–	–	–	–
Berberis integerima	–	–	–	–	–
Prunus pseudoprostrata	–	–	–	–	–
Tanecetum polycephalum subsp. *duderanum*	–	–	–	–	–
Veronica intercedens	–	–	–	–	–
Alyssum stapfii	–	–	–	–	–
Noccaea platycarpa	–	–	–	–	–
Cephalaria microcephala	–	–	–	–	–
Rosularia radicosa	–	–	–	–	–
Ziziphora clinopodioides	–	–	–	–	–
Cotta triumfetti	–	–	–	–	–
Euphorbia microsciadia	–	–	–	–	–
Hedlundia persica	–	–	–	–	–
Tragopogon collinus	–	–	–	–	–
Orobanche caryophyllacea	–	–	–	–	–
Aethionema carneum	–	–	–	–	–
Stellaria kotschyana	–	–	–	–	–
Alyssopsis mollis	–	–	–	–	–
Teucrium chamaedrys	–	–	–	–	–

Table 2 (continued)

Community number	CT1	CT2	CT3	CT4	CT5
Allium aladaghense	–	–	–	–	–
Centaurea rhizantha	–	–	–	–	–
Prunus microcarpa	–	–	–	–	–
Vicia sativa	–	–	–	–	–
Allium cristophii	–	–	–	–	–
Bongardia chrysogonum	–	–	–	–	–
Juniperus polycarpos var. *turcomanica*	–	–	–	–	–
Lonicera floribunda	–	–	–	–	–
Cephalaria bodjnurdens	–	–	–	–	–
Gagea robusta	–	–	–	–	–
Securigera varia	–	–	–	–	–
Linaria golestanensis	–	–	–	–	–
Alyssum murale	–	–	–	–	–
Lonicera bracteolaris	–	–	–	–	–
Echinops ritrodes	–	–	–	–	–
Silene bojnordensis	–	–	–	–	–
Erysimum ischnostylum	–	–	–	–	–
Juniperus communis	–	–	–	–	–
Allium sarawschanicum	–	–	–	–	–
Rubia rechingeri	–	–	–	–	–
Allium kopetdaghense	–	–	–	–	–
Inula aspera	–	–	–	–	–
Artemisia kopetdaghensis	–	–	–	–	–
Nepeta bodeana	–	–	–	–	–
Galium sp.	–	–	–	–	–
Rosa iberica	–	–	–	–	–
Tulipa montana	–	–	–	–	–
Tulipa hoogiana	–	–	–	–	–
Pseudotrachydium kopetdaghense	–	–	–	–	–
Astragalus oxyglottis	–	–	–	–	–
Minuartia hybrida	–	–	–	–	–
Onosma dichroantha	–	–	–	–	–

Based on the CCA analysis graph (Fig. 5), soil and topography variables had significant effects on the composition of plant communities in the study area. In more detail, the eigenvalues of the first seven axes were 0.57, 0.49, 0.27, 0.21, 0.17, 0.08, and 0.05, respectively (Table S2), which together explained 83.1% of the total variation in the environmental variables. Some variables were eliminated from the environmental data set owing to high collinearity (VIF > 10), including nitrogen, clay, phosphorus, organic matter, organic carbon, sand, aspect, and slope. The seven remaining environmental variables included pH, percentage of neutralizing agents (TNV), moisture, silt, electrical conductivity (EC), K percentage, and elevation, all of which were significant ($P > 0.05$; Table 3). The data of soil properties are shown in Table S3 for the samples collected from the plant communities associated with *Cousinia edmondsonii.*pH, EC, and TNV had the highest correlations with the communities CT3, CT4, and CT5; in these, *Cousinia edmonsonii* has the highest dominance and cover percentage. Percentage of silt was positively correlated with community CT2 and with the four plots of community CT5. Percentage of humidity had a high correlation with community CT1. The amount of potassium was also correlated with one of the plots of communities CT3 and CT4. The comparison of the explained variance values (constrained inertia = 2.68) by CCA axes compared to the total variance (total inertia = 4.90) shows that a large amount (about 54.58%) of the changes in the distribution pattern of the vegetation composition was described by the selected environmental variables in this research. The pH with $r^2 = 0.62$ and K with $r^2 = 0.21$ had the highest and lowest values, respectively.

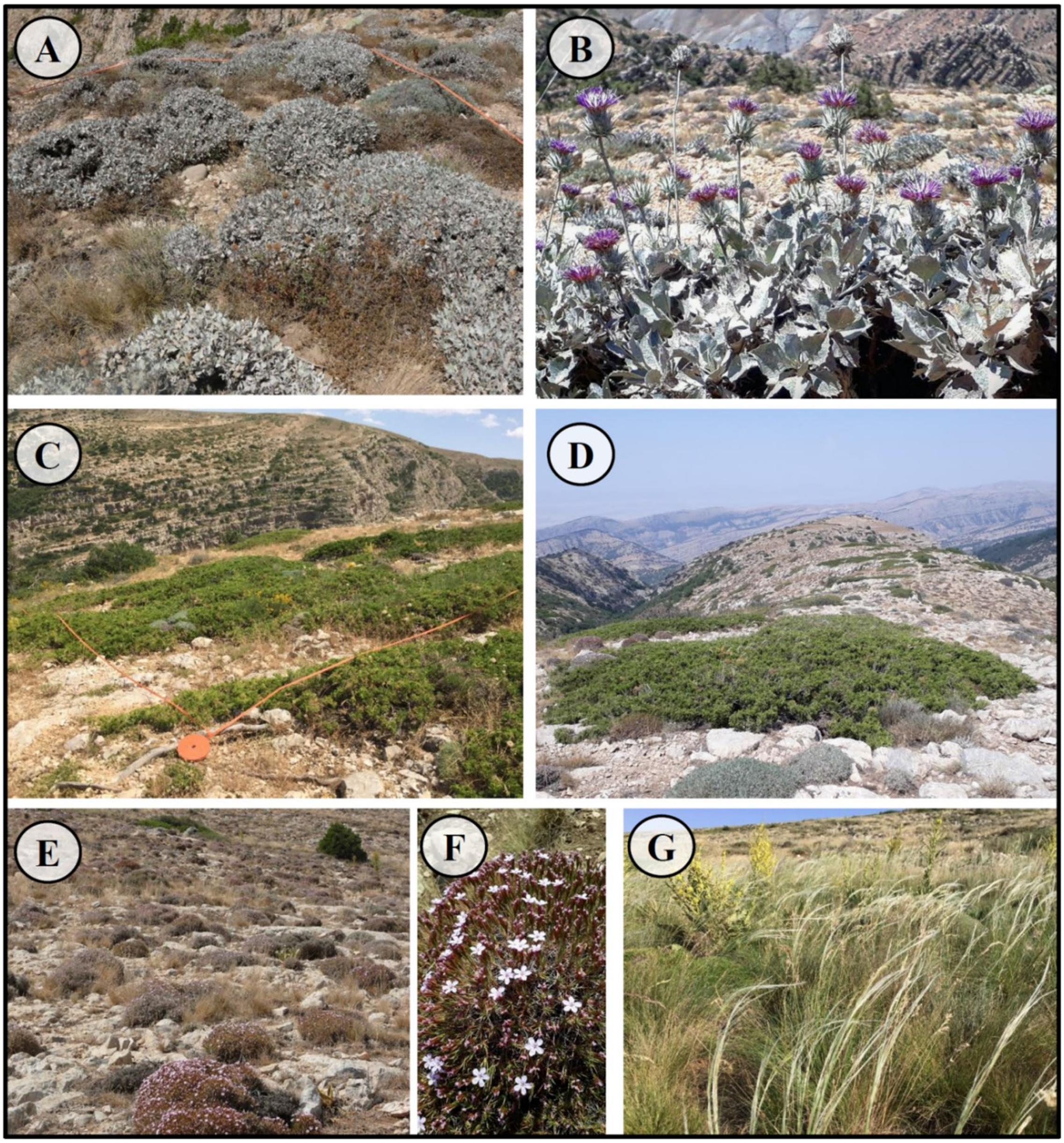

Fig. 3 A selection of some typical sub-alpine communities in western Aladagh Mountains: **a** and **b**, *Cousinia edmondsonii*; **c**, *Juniperus communis*; **d**, *Juniperus sabina*; **e** and **f**, *Acantholimon erinaceum*; **g**, *Stipa lessingiana*

Diversity analysis between the plant communities

Based on the Hill numbers (N_0, N_1, N_2) graph (Fig. 6), community CT1 with cushion plants indicated more species diversity than community CT2 with creeping *Juniperus sabina*. Communities CT3, CT4, and CT5, with dominance of *Cousinia edmondsonii*, had higher species diversity than plant communities CT1 and CT2.

Reassessment of conservation status of Cousinia edmondsonii

Based on newly recorded populations from western Aladagh Mountains, the area of occupancy (AOO) and extent of occurrence (EOO) of *C. edmondsonii* are increased up to

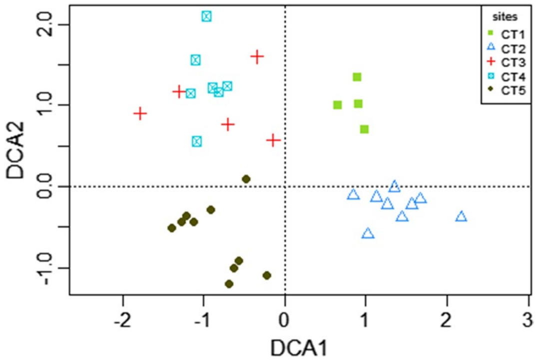

Fig. 4 DCA ordination of 35 sample plots on axes 1 and 2 for the 5 communities based on species composition

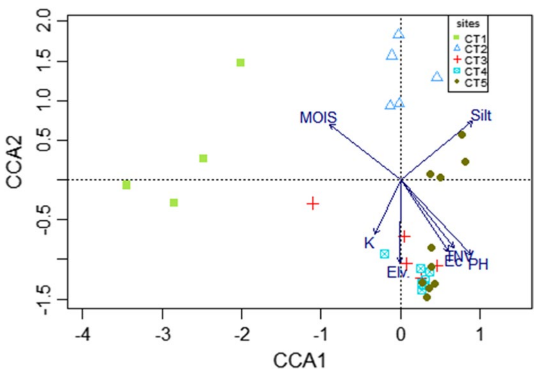

Fig. 5 CCA ordination of the first two axes showing the distribution of the 35 plots for the five communities. Soil variables (K = potassium; pH; TNV; EC; Silt; Mois = moisture) and topography (Elv. = elevation).

Table 3 Significance and correlation between environmental variables and CCA analysis

	CCA1	CCA2	r2	Pr (> r)	
Silt	0.77683	0.62971	0.5075	0.001	***
PH	0.68825	− 0.72547	0.6273	0.001	***
Ec	0.55607	− 0.83114	0.4345	0.001	***
TNV	0.62359	− 0.78175	0.4356	0.001	***
K	− 0.43369	− 0.90106	0.2101	0.035	*
MOIS	− 0.7862	0.61797	0.4819	0.001	***
Elv	− 0.00877	− 0.99996	0.4063	0.004	**

* statistically significant at 5% level

** statistically significant at 1% level

***statistically significant at 0.1% level

12.00 and 42.53 km^2, respectively (Fig. 7). Although the AOO of the species falls in threshold for Endangered (EN) category, it is re-evaluated as Critically Endangered (CR) because of spatial thresholds of EOO (IUCN, 2019).

Discussion

The mountain steppe vegetation in Khorassan-Kopet Dagh inhabits several local and narrow endemic plants that many of them are threatened. In this paper, we aimed to classify vegetation, evaluate floristic composition, and compare diversity indices and habitat characteristics of the plant communities hosting the Red Listed species *Cousinia edmondsonii*. Based on the floristic results, different species composition and life-forms are manifested among the studied communities. The floristic composition of the study area shows the dominance of Angiosperm families Asteraceae, Brassicaceae, Fabaceae, Poaceae, and Lamiaceae and a 4:1 ratio of Dicots to Monocots which is typical of Irano-Turanian flora (Kamakhina, 1994). The majority of species in the study sites displayed life-form as hemicryptophyte which indicates the cold and semi-arid conditions in mountain steppe vegetation (Rabiei et al. 2009; Klimes 2003). Chamaephytes, as the second dominant life-form in the study area, include the thorn-cushion species that they are another characteristic of higher mountain vegetation. Similar floristic composition and life-form spectrum have been shown in several mountainous areas of KK Floristic Province (Amiri et al., 2022; Atashgahi et al., 2018; Behroozian et al., 2022; Memariani et al., 2016c).

The classification analyses indicated a clear separation of plant communities in the study area, which was confirmed by DCA. The target species *Cousinia edmondsonii* is associated with two communities (CT1 and CT2), which they are dominated by thorny cushion species *Acantholimon erinaceum* and dwarf shrubby species *Juniperus sabina*, respectively. These communities consists of an almost homogeneous structure with low species diversity. However, *C. edmondsonii* is a dominant species in three other communities (CT3, CT4, and CT5) with the highest diversity indices in the study area. This species provides favorable conditions for other species thanks to its relatively high cushion-form habit, dense vegetation cover (up to 70 percent), high wind resistance, and appropriate soil depth. As a distinctive landscape feature, vegetation has been a fundamental component of land classifications (Daubenmire, 1943). Recently, vegetation classification has been emphasized as a communication tool in ecological research and in the application of ecological information in planning, monitoring, conservation, and management (Jennings et al., 2009).

The results showed that the composition of plant communities was significantly correlated with some topographic and environmental factors. The high correlation of CT1 with soil moisture indicates a direct relationship with low slope, sufficient soil depth, and distribution of trapped clouds coming up from the lower elevations. There is a high rate of slope changes topographically from 1000 to 2000 m in the

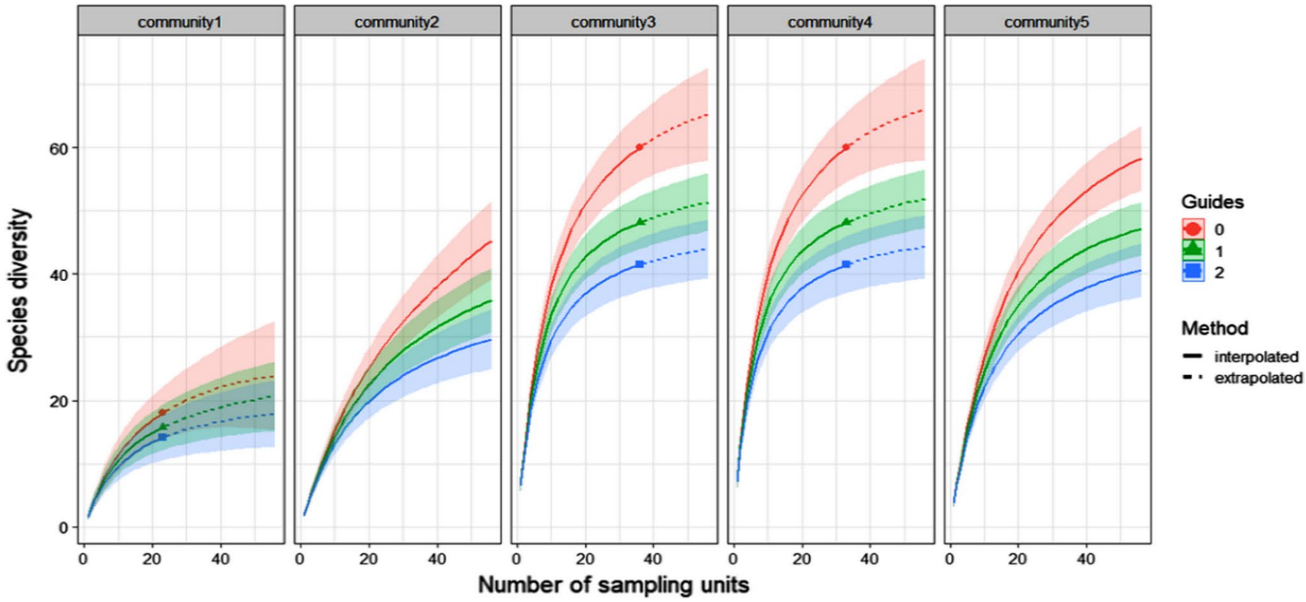

Fig. 6 Hill numbers of the 35 plots on the five communities in the analysis of plant community variation actoss the Aladagh and Ghorkhod Mountains.

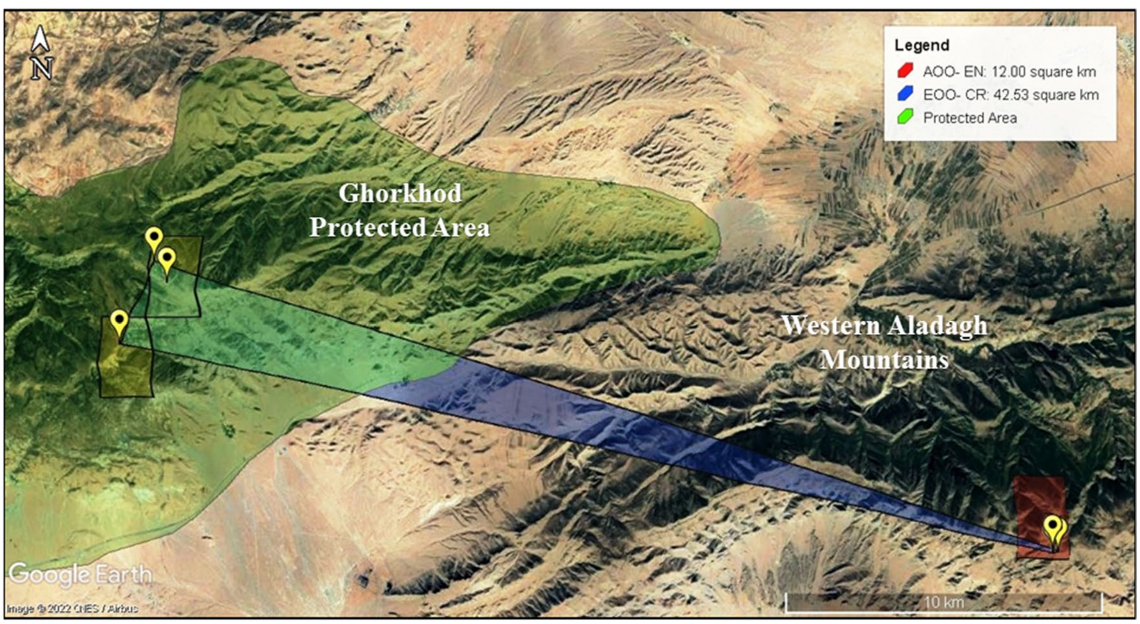

Fig. 7 GeoCAT distribution map of *Cousinia edmondsonii* in NE Iran and estimation of Area of Occupancy (AOO) and Extent of Occurrence (EOO), with maximum distance of 30 km between pairs of points, based on IUCN Red List Criteria

west of Aladagh, which makes for strong barriers to the passage of clouds from the west (Fig. 1c, 7); accordingly, clouds are trapped for a long period, increasing moisture and forming a dense forest of *Quercus castaneifolia* in this elevation range. Community CT1 contains gentle slope changes at elevations above this dense forest, between 2000–2380 m. The studies show that soil context plays an important role in controlling the amount of moisture and available nutrients for plant roots; such that the soils with suitable depth and light-textured soils can provide enough water for plants (Brady & Weil, 2002). All plots of community CT2 and four plots from community CT5 showed high correlations with soil silt percentage and a lower correlation with moisture. *Juniperus sabina* is the dominant or associated species in these communities, which occurs over bedrock with low soil depth and high silt percentage. These communities are located in 2000–2100 m, and thus they are affected by the moisture of lower elevations. However, soil moisture had a low correlation with these communities due to rocky beds and low soil depth. Elevation, TNV, EC, pH, and potassium percentage were positively correlated with communities CT3, CT4, and CT5 where *C. edmondsonii* is the dominant species (Fig. 5, Table S3); therefore, these factors likely play important roles in forming these communities. Potassium, nitrogen, and phosphorus are the most important micronutrients in soil ecosystems (Diekmann, 2003) and a good indicator of productivity and nutrient availability in the habitats (Duru et al., 2010). The soil alkalinity is a prominent feature of calcareous soils. TNV rate depends on magnesium carbonate and calcium carbonate content of the soil. *C. edmondsonii* communities (CT3, CT4, and CT5) geologically include limestone and dolomitic bedrock, which have a high percentage of magnesium carbonate and calcium carbonate, following pH and EC (Rayburn, 2014).

Conclusion

The results reflect the highly diverse flora in the studied sub-alpine communities. The area is located in one of the plant biodiversity hotspots in the Irano-Turanian region. The natural vegetation of this area is strongly correlated with soil and topographic factors such as elevation, the total neutralizing value of the limestone, soil EC, pH, soil moisture, and percentage of potassium and sand; all influenced distribution of species. Plant communities dominated by *Cousinia edmondsonii* exhibited higher species diversity. These communities are highly correlated with the elevation and total neutralizing value of the limestone. The results showed that *C. edmondsonii* as an endemic and critically endangered species, its habitats, and diversified vegetation types in the higher mountains of western Khorassan-Kopet Dagh deserve special conservation attention.

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Data availability Not Applicable.

Declarations

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Consent to participate/publish (ethics) All participating authors consent to participation and publication.

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