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ABSTRACT
High-resolution vegetation maps, at 1:500 scale, were realized in three mires located in the Italian south-eastern Alps (Coltrondo West, 12,800 m^2; Coltrondo South, 22,300 m^2 and Palù di sotto, 50,600 m^2). Vegetation maps were based on topography surveyed by GPS, performed on ground surveys and produced using ArcGIS 9.1. A total of 36 plant communities, whose distribution was reported on the maps, were individuated and classified according to the Braun-Blanquet method. The mires strongly differed from each other with regard to vegetation cover, with Coltrondo West having a prevalent bog-like vegetation and Coltrondo South a prevalently fen-like vegetation. At Palù di sotto, bog-like vegetation covered a surface fed by ground water. This pattern could be explained by the lowering of water table determined by intensive water extraction for human activities. The maps will be profitably used as reference for future monitoring of vegetation dynamics under changing climatic and landuse conditions.

1. Introduction

Microtopography falls within the broader notion of topographic heterogeneity, which comprises patterns of elevation at different spatial scales formed by geologic, hydrologic, physical and biological processes (Larkin, Vivian-Smith, & Zedler, 2006). Although it has been used frequently in vegetation studies for decades, plant ecologists only recently proposed a definition of microtopography as a combination of features constituting a local terrain surface covering elevation differences up to 5 m (Moeslund, Arge, Bøcher, Dalgaard, & Svenning, 2013). The influence of microtopography on local vegetation patterns was reported for a large number of both dry and wet habitats. In wetlands, microtopography influences habitat diversity especially in boreal and temperate peatlands, where it is important in determining plant species distribution and, ultimately, ecosystem functioning (Moser, Ahn, & Noe, 2007). Small-scale surface patternings, resulting in a typical microtopography of hummocks and hollows, occur especially in bogs and transitional mires, where they are generally created by the varying growth forms of differing moss species belonging to the genus *Sphagnum* and by differences in rates of organic matter production and decomposition (Belyea & Clymo, 2001; Bubier, Moore, & Crosby, 2006). These microtopographic patterns influence the water-table level over short distances providing an important range of small-scale micro-environments

and vegetation patterns. For these reasons, current models and theories on the formation and maintenance of microtopography in ombrotrophic peatlands assume autogenic feedbacks between vegetation composition, water-table depth and microtopography (Malhotra, Roulet, Wilson, Giroux-Bougard, & Harris, 2016).

Peatlands are extensively distributed in the boreal and subarctic regions of the northern hemisphere, while they are only a minor component of the landscape in mid-latitude regions, where they cover a modest fraction of the territory and are concentrated on montane areas (Mitsch & Gosselink, 2000). Nevertheless, these temperate peatlands possess a remarkable scientific and conservation importance because they host several endangered species (Bragazza, 2009; Gerdol & Tomaselli, 1997) and habitats of community interest that are worthy to be preserved under the Habitats Directive (92/43/EEC of 1992) and are protected in the European Natura 2000 network, including Sites of Community Importance (SCI) (European Commission, 2013).

Peatlands in Italy are most abundant in the southern Alps and in the northern Apennines. Several studies have recently dealt with these habitats focusing on floristic composition and vegetation patterns, also in relation to water-table position and nutrient status (Gerdol, 1990; Gerdol et al., 2011; Gerdol & Tomaselli, 1993; Gerdol, Tomaselli, & Bragazza, 1994; Petraglia & Tomaselli, 2003).

In the last few decades, peatland cover declined because of environmental changes proceeding at unprecedented rates as an effect of climate warming and human activities (Gerdol, Bragazza, & Brancaleoni, 2008). Climate change will have severe implications for the biodiversity of these ecosystems because peatland vegetation is likely to change over time towards drier communities, only some of which being able to accumulate peat (Dise, 2009). As a consequence, periodic monitoring of vegetation patterns in these ecosystems could be strategic for assessing the integrity of plant communities, planning conservation measures and providing a baseline for restoration options (Schumann & Joosten, 2008).

Plant communities of peatlands have distinct infrared signatures, which means that at the coarse scale, it is possible to distinguish them from forest and grasslands using remote sensing techniques such as satellite imagery or aerial photography (Poulin, Careau, Rochefort, & Desrochers, 2002). However, while it would be possible to use these techniques to detect the distribution of plant communities in boreal peatlands where they cover large surfaces, it is practically impossible to use this methodology to detect small-scale vegetation patterns occurring in temperate peatlands.

Vegetation mapping based on direct field inspections is not an easy task as these habitats generally encompass a variety of plant communities, often forming complex vegetation mosaics. Such extreme microhabitat patchiness and small-scale heterogeneity create problems for representing the distribution of vegetation units frequently smaller than a few square-metres on vegetation maps that could be therefore relatively prone to inaccuracy. On the other hand, high-resolution vegetation maps provide indirect information on the ecology of peatlands that can be useful for the management of these extremely vulnerable ecosystems, strongly depending on delicate equilibria among water input, nutrient loading and climate (Rydin & Jeglum, 2006).

In this perspective, high-resolution periodical mapping of peatland vegetation can be an invaluable tool for providing information on environmental features that may not be easily discernible based on field inspection. High-resolution periodic mapping of peatland vegetation can also highlight dynamic trends reflecting long-term hydrological changes.

Vegetation mapping can adequately serve this purpose when vegetation types are sampled at a high floristic resolution up to the level of sub-communities or variants differentiated by the composition of the bryophyte layer. In this way, also slight changes in the floristic composition of bryophyte composition of vegetation types reflecting hydrological changes can be detected in future monitoring.

The goal of this study was to document the present vegetation patterns in three different types of peatlands designated as SCI, lying in the south-eastern Alps. The sites were selected because they were in good ecological condition and differed in their management history.

2. The study mires

The study was carried out during the years 2005 and 2006 at three mires in the south-eastern Alps of Italy. Two of the mires (Coltrondo West, CW and Coltrondo South, CS) are situated in the north-eastern Dolomites, about 700 m apart (Coltrondo, municipality of Comelico superiore; 46°40′N, 12°27′E; Figure 1). The third mire (Palù di sotto, PS) is situated in the western Venetian Prealps (Marcesina, municipality of Enego; 45°58′N, 11°37′E; Figure 1). The bedrock at CW and CS consists of phyllites and sandstones of late Paleozoic age (Regione Veneto, 1992–2017). The chemistry of both parent materials is acidic and poor in calcium. The climate in the Coltrondo area is cool, with a mean annual temperature of ca 4°C and mean total annual precipitation of ca 1200 mm. The bedrock at PS consists of lime-rich limestones of late Jurassic–Cretaceous age, overlaid by impermeable clayey glacial deposits (Regione Veneto, 1992–2017). The chemistry of the clayey matrix is acidic and poor in calcium. Also at this site, the climate is cool, with a mean annual temperature of ca 4°C and mean total annual precipitation of ca 1500 mm.

The three mires differ from each other based on hydromorphological features (*sensu* Økland, 1989). CW (elevation 1830 m; area 12,800 m^2) lies on a saddle and has a peat thickness barely exceeding 2.5 m. CW is mostly covered by bog-like vegetation and falls into the type of unilaterally sloping bogs, usually called ombrosoligenous bogs in the Alps (Kaule, 1974). CS (elevation 1790 m; area 22,300 m^2) lies in a structural elongated basin, with a small perennial creek draining the mire. The thickness of the peat body attains 7 m in the central part of the mire. CS is covered by a mosaic of bog-like hummocks and by large flat areas with fen-like vegetation. CS hence falls into the type of transitional mires. PS (elevation 1330 m; area 50,600 m^2) lies in a basin of karstic origin. The thickness of the peat body attains 4 m in the central part of the mire. PS is mostly covered by bog-like vegetation with a narrow marginal fen-like rim. PS probably falls into the type of raised bogs although it suffered historical damage by grazing and is presently subject to water extraction.

3. Methods

Mapping of peatland habitat and vegetation cover was based on ground-based surveys using a detailed topographic map. The topography of the three mires was surveyed by GPS, using two Leica SR 530 double frequency receivers working in real-time kinematics (RTK) modality. This procedure allowed for a large set of
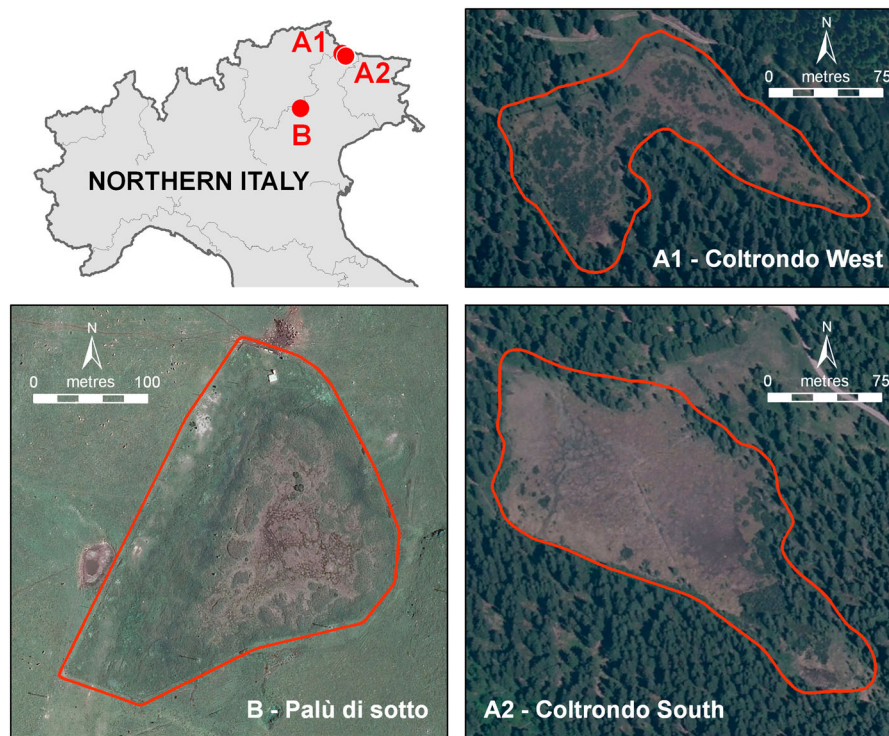
Figure 1. Geographic location and general vision of the studied mires. Orthophotos of mire areas were taken from the website 'Geoportale nazionale'.

high accuracy data in reasonable time. The reference benchmarks for RTK surveys were preliminarily set up by static relative positioning and subsequent post-processing the data with those collected at the closest permanent station (Bolzano, Bozen; BZRG). About 1000 topographic points were georeferenced at each mire, with an average accuracy of 0.6, 0.8 and 1.6 cm, for latitude, longitude and elevation, respectively. The topographic points were mostly arranged according to a regular grid in each of the three mires. About 5% the points were chosen subjectively in order to account for the high topographic heterogeneity of some areas. Detailed contourings (10-cm spacing) and digital elevation models (DEMs) were obtained for all mires using the Program Surfer 8 (Golden Software Inc.). Contourings were obtained by kriging interpolation with default linear variogram using the program Surfer 8.

As our maps were conceived for monitoring mire vegetation over time, it is important to understand if and to what extent our data can be effectively used for comparison in future mapping. A possible source of bias in periodic monitoring of mire habitats consists in varying surface topography. Indeed, the surface of mire can rise and fall over time due to the spongy feature of the peat body (Dise, 2009). Such so-called bog breathing may imply periodic changes in mire surface elevation. It is impossible to predict the extent to which the surface of the three mires is subjected to fluctuations in the absence of data on pore-pressure profiles in the peat bodies (Reeve, Glaser, & Rosenberry, 2013). However, changes in mire surface elevation are closely related to precipitation. The topographic survey was

carried out on different dates in the three mires (CW and CS: 11–12 August 2005; PS: 17 August 2005). We compiled a table including data on daily air temperature and precipitation in the growing season (June–September 2005), collected at two weather stations located at Coltrondo and Marcesina, respectively. The table is available as supplemental material. These data are useful for scheduling future monitoring under weather conditions as similar as possible to those experienced during the 2005 mapping.

The vegetation of the three mires was surveyed in summer 2005 and the distribution of vegetation types was mapped in summer 2006, using the previously realized topographic maps as a basis. The floristic composition of vegetation was surveyed using the cover-abundance scale proposed by Braun-Blanquet (1964) at a number of plots (vegetation records) whose size ranged from 1 m^2 (hummocks and pools) to 100 m^2 (wet grasslands and wet coniferous forests). Vegetation types were defined by numerical grouping of vegetation records. Clustering was based on the similarity ratio index and was performed with Unweighted Pair Group Method with Arithmetic Mean (UPGMA). The package SYN-TAX 2000 (Podani, 2001) was used for computations.

The vegetation types defined by the numerical classification were subsequently classified according to the standard procedures of the Zürich-Montpellier School (Braun-Blanquet, 1964) and assigned, whenever possible, to the phytosociological units reported in the most recent studies on mire vegetation performed in the eastern Alps (Conradi & Friedmann, 2013;

Dierssen, 1980; Dierssen, 1998; Gerdol & Tomaselli, 1993; Dierssen & Dierssen, 2008; Lederbogen, 2003; Steiner, 1992). Vegetation types of lower rank than association were differentiated by the dominant species in the bryophyte layer, indicating different water levels within the association as suggested by Dierssen (1980). They were classified as sub-associations whenever documented in the literature. Alternatively, they were documented as variants when not previously documented in the literature. We adopted the term 'community of' followed by the name of the dominant species to define vegetation units that could not be referred to an association in the absence of true character species.

Species nomenclature follows Aeschimann, Lauber, Moser, and Theurillat (2004) for vascular plants and Aleffi, Tacchi, and Cortini Pedrotti (2008) for bryophytes. Nomenclature of vegetation types follows Steiner (1992) for the mire plant communities and to Grabherr and Mucina (1993) for the other communities.

Vegetation mapping was performed with two GPS instruments (Trimble Pathfinder Pro XRS and Trimble GeoXT, base station and rover receivers, respectively, Figure 2). During the mapping campaigns, the base station was placed at the centre of each mire to collect data used for subsequent post-processing. In this way, we obtained data with a precision of 10 cm. Finally, the topological integrity constraint was verified with GIS elaboration of the data and gaps and/or overlaps occurring within polygons were corrected. Vegetation types were represented on the maps as polygons when their surface exceeded or was equal to 0.25 m^2, and as points when their surface was lower. Besides plant communities, we mapped the location of individual seedlings and adult trees in order to monitor tree colonization.

4. Results and discussion

Overall, 36 different vegetation types were identified in the three mires (Table 1). Four of them were directly identified in the field without making vegetation records because these vegetation types corresponded to well-known grassland and forest associations (Sieverso-Nardetum strictae, Alnetum viridis, Larici-Piceetum) or to an undefined Molinio-Arrhenatheretea community. The 32 remaining vegetation types were defined by numerical classification of 119 vegetation records. Of them, 26 were classified as associations, sub-associations and variants, whereas 6 could not be referred to any association, because they lacked true character species.

A dendrogram and a synoptic table documenting results of the numerical classification up to the level of 20 associations and communities were provided as supplemental materials Among the 36 vegetation types detected, 26 were regarded as true peatland communities. The remaining nine vegetation types only occasionally occur in peatlands mostly due to disturbance and/or to dynamic processes towards drier habitats. Five of these vegetation types were scrub and forest communities, while four of them corresponded to different types of grasslands. The mires occurring in the north-eastern Dolomites showed a remarkable richness in plant communities. In particular, CW included more vegetation types than CS (21 against 19), despite its lower surface. PS was poorer in plant communities (only 14 vegetation types). This could be explained considering both that PS lies at a southernmost outpost of these habitats in the Alps and that it underwent severe human impact.

CW showed a peculiar horseshoe shape (Figure 1). The most widespread plant community throughout the mire was the scrub vegetation dominated by Pinus mugo (Pino mugo-Sphagnetum magellanici), covering about half of the mire surface (Figure 3; higher-left side of the Main Map). Other communities dominated by shrubs or trees were the scrub vegetation co-dominated by Rhododendron ferrugineum and Pinus mugo (Rhododendro ferruginei-Pinetum prostratae) and the spruce woodland (Larici-Piceetum) occurring at the most raised sites. Particularly abundant and widespread were also the uniformly raised areas where the ground layer was dominated by the mosses Sphagnum capillifolium and Sphagnum fuscum, while the field layer consisted of a mixture of dwarf shrubs and graminoids (Sphagnetum magellanici with S. capillifolium and Sphagnetum magellanici sphagnetosum fusci). The eastern part of the mire was colonized by lawns including a

Figure 2. The two GPS instruments, Trimble Pathfinder Pro XRS and Trimble GeoX, used as base station and rover receivers, respectively, for vegetation mapping.

Table 1. Percentage cover of vegetation types in the studied mires.

Vegetation types	Mires		
	CW	CS	PS
Utricularietea intermedio-minoris			
Scorpidio-Utricularietum minoris		<0.01%	
Scheuchzerio-Caricetea nigrae			
Scheuchzerietalia palustris			
Caricetum limosae typicum	0.1%		
Caricetum limosae variant of *Cladopodiella fluitans*	0.5%		
Caricetum limosae variant of *Gymnocolea inflata*		<0.01%	
Caricetum limosae variant of *Scorpidium cossonii*		1.1%	
Caricetum rostratae typicum	1.0%	0.4%	1.4%
Caricetum rostratae variant of *Campylium stellatum*		1.3%	
Caricetum rostratae variant of *Scorpidium cossonii*		0.5%	
Caricetum rostratae variant of *Sphagnum subsecundum*	1.5%	0.7%	2.0%
Caricetum rostratae sphagnetosum fallacis	0.8%	0.01%	
Caricetum rostratae sphagnetosum flexuosi			0.5%
Community of *Eriophorum angustifolium*	<0.01%		0.7%
Caricetalia nigrae			
Caricetum nigrae typicum	4.6%	0.1%	
Caricetum nigrae sphagnetosum subsecundi	1.5%		
Caricetum nigrae sphagnetosum girgensohnii	0.4%		
Menyantho trifoliatae-Sphagnetum teretis	2.8%	22.4%	
Caricetalia davallianae			
Drepanoclado revolventis-Trichophoretum cespitosi	0.3%	22.3%	
Drepanoclado revolventis-Trichophoretum cespitosi variant of *Gymnocolea inflata*		4.2%	
Campylio-Caricetum dioicae		0.03%	
Community of *Carex nigra*			3.1%
Community of *Carex panicea*			0.6%
Oxycocco-Sphagnetea			
Sphagnetum magellanici typicum		0.1%	21.8%
Sphagnetum magellanici sphagnetosum fusci	1.7%		0.7%
Sphagnetum magellanicum variant of *Sphagnum capillifolium*	25.7%	27.3%	3.0%
Eriophoro vaginati-Trichophoretum cespitosi	11.0%		
Pino mugo-Sphagnetum magellanici	40.1%	11.1%	0.3%
Caricetea curvulae			
Sieversio-Nardetum strictae	0.8%	1.2%	
Molinio-Arrhenatheretea			
Community of *Molinia caerulea*			10.7%
Community of *Molinia caerulea* with dried *Sphagnum capillifolium* hummocks			14.5%
Community of *Deschampsia caespitosa*			18.1%
Community of Molinio-Arrhenatheretea			22.5%
Mulgedio-Aconitetea			
Alnetum viridis		0.2%	
Loiseleurio-Vaccinietea			
Rhododendretum ferruginei		1.1%	
Vaccinio-Piceetea			
Larici-Piceetum	1.8%	5.2%	
Sphagno girgensohnii-Piceetum	1.9%	0.6%	
Rhododendro ferruginei-Pinetum prostratae	3.5%		

Note: CW: Coltrondo West; CS: Coltrondo South; PS: Palù di sotto.

mixture of *Sphagnum* mosses (mostly *Sphagnum magellanicum* and *S. compactum*) and vascular plants, mostly graminoids with *Trichophorum caespitosum* as the dominant species (*Eriophoro vaginati-Trichophoretum caespitosi*). The lawns included hollows with a rather sparse vascular cover, where the sedges *Carex limosa* and *Carex rostrata* were alternatively dominant, settled on a ground layer of brown mosses and/or *Sphagnum* mosses, or directly on the bare peat (*Caricetum limosae* and *Caricetum rostratae* with several variants). Alongside its eastern side, the mire was delimited by a marginal stream, where vegetation consisted of a mixture of graminoids and forbs dominated by *Carex nigra* (*Caricetum nigrae typicum*). Finally, some small areas in the south-eastern part of the mire were colonized by fen meadows (*Drepanoclado revolventis-Trichophoretum cespitosi* and *Menyantho trifoliatae-Sphagnetum teretis*). The vegetation map confirmed that CW could be regarded as an ombrosoligenous bog, as also

documented by water flow patterns and water chemistry (Gerdol et al., 2011). The high cover of scrub and woodland vegetation suggested a trend of water-table lowering which enhances the invasion of woody species at the expense of bog specialists (Smith, Lunn, & Newson, 1995).

CS had an approximately ellipsoidal shape (Figure 1). Moreover, it was gently inclined from North to South. The most widespread community was a fen meadow colonizing the central part of the mire (Figure 4; lower-left side of the Main Map). It had a ground layer mostly formed of brown mosses and a field layer consisting of a mixture of graminoids and forbs (*Drepanoclado revolventis-Trichophoretum cespitosi*). The wettest area in this community was differentiated by the high frequency of the liverwort *Gymnocolea inflata*. The central part of the mire also hosted a number of small hummocks, interspersed with the fen lawns. These hummocks possessed a ground layer dominated

Figure 3. Coltrondo West mire.

by *S. capillifolium* and a field layer with a mixture of dwarf shrubs and graminoids (*Sphagnetum magellanici* with *S. capillifolium*). Along the northern and southern border of the fen meadow, the hummocks merged to form larger raised areas. Hollows occurred mostly at the north-western gently sloping portion of the fen. Their field layer was alternatively dominated by the sedges *C. limosa* and *C. rostrata*. In this part of the mire, there were also some pools with the rare species *Utricularia minor* (*Scorpidio-Utricularietum minoris*).

Figure 4. Coltrondo South mire.

They covered very small areas and, hence, were indicated only as points on the map. Another abundant fen community in CS was the *Menyantho trifoliatae-Sphagnetum teretis* that bordered the western and southern sides of the mire. Scrub and woodland communities (*Pino mugo-Sphagnetum magellanici, Rhododendretum ferruginei, Sphagno girgensohnii-Piceetum, Larici-Piceetum, Alnetum viridis*) were here confined to the raised borders and the south-eastern part of CS. In this latter portion, the *Pino mugo-Sphagnetum magellanici* and the *Larici-Piceetum* occurred on a raised area separating the main body of the mire from a south-eastern outpost covered by a fen meadow (*Menyantho trifoliatae-Sphagnetum teretis*). CS was mostly covered by fen meadows. Hydrology, water chemistry and vegetation composition clearly indicated minerogenous conditions (Gerdol et al., 2011). However, part of this mire was covered by vegetation types closely resembling those occurring at the CW bog, especially hummocks and scrubs. Nevertheless, water chemistry did differ considerably between the two sites, with pore-water in CW being more acidic and poorer in dissolved ions compared with CS (Gerdol et al., 2011). The CS mire could, therefore, be regarded as a moderate-rich fen, although the portion covered with *Sphagnum* hummocks had the features of a 'transitional mire' between acid bogs and alkaline fens (Ellenberg & Leuschner, 2010).

The vegetation map of PS included not only the true peatland but also the surrounding areas delimited by an iron fencing placed for preventing cattle entering the mire (Figure 1). The vegetation of these areas was strongly altered in the past by grazing and is still nowadays affected by water extraction. The mire had a triangular shape. The central part of the mire was occupied by a *Sphagnum* lawn where *S. magellanicum* largely prevailed (*Sphagnetum magellanici typicum*) (Figure 5; right side of the Main Map). Both hummocks and hollows were interspersed with the *Sphagnetum magellanici* lawns in this part of the mire. The hummocks were ascribed to two different communities: the *Sphagnetum magellanici sphagnetosum fusci* and the *Sphagnetum magellanici* with *S. capillifolium*. The hummocks of the latter community were taller and mainly occurred at the periphery of the fen meadow, where they formed a raised fringe representing a clear transition to the drier surrounding areas. The few driest tallest hummocks invaded by *Pinus mugo* were classified as stands of the *Pino mugo-Sphagnetum magellanici*. The hollows were colonized by two main different sedge-dominated plant communities. The former, largely occurring inside the *S. magellanicum* carpet, was characterized by the dominance of *C. rostrata* and showed a certain floristic variability. The floristically poorer stands were ascribed to the *Caricetum rostratae typicum* and were mainly distributed in the northern and eastern part of the mire. Other stands had a cover of *C. rostrata* over a carpet of semi-aquatic *Sphagna* (*Sphagnum subsecundum* and *Sphagnum flexuosum*). The hollows with *S. subsecundum* were concentrated in the southern part of the mire and were larger and more frequent, while the hollows with *S. flexuosum* occurred more sporadically in the eastern part of the

Figure 5. Palù di sotto mire.

mire. The central part of the mire included an extensive pool area, where bare peat was colonized by the sedge *Eriophorum angustifolium* and few other vascular and moss species (community of *Eriophorum angustifolium*). Alongside the central *S. magellanicum* carpet, vegetation showed degradation characteristics probably because of combined effects of grazing, draining and water extraction. Here, the peat-building *Sphagna* tended to fade in importance, surviving sporadically as raised areas derived from the confluence of the remnants of dried *S. capillifolium* hummocks and being mostly replaced by ericoid shrubs (mostly *Calluna vulgaris*). The latter formed a mosaic with swards dominated by *Molinia caerulea*. PS did not include woodland communities. The occurrence of individual trees was restricted to the disturbed areas between the peatland and the iron fencing. The vegetation cover of the peatland area of PS, with its intricate mosaic of lawn and hummocks, resembled that of the ombrogenous bogs. Nevertheless, hydrology and water chemistry suggested that the mire was prevalently fed by ground water (Gargini, Viaroli, Tomaselli, & Gerdol, unpublished report, 2006). The inconsistency between vegetation patterns and hydrology was probably determined by water extraction for human activities. Water withdrawal likely determined a lowering of the water table which made the vegetation substantially fed by rainwater. This may trigger dynamic processes implying gradual replacement of bog species with fen species.

Software

The software SKI-Pro LeicaGeosystem was used for the post-processing GPS data concerning the topographic maps. For producing them, we used the Program Surfer 8 (Golden Software Inc.). The software Trimble Pathfinder Office 2.9 was used for the post-processing GPS data concerning the vegetation maps. The Program ESRI ArcMap 9.1 was used for both digitizing vegetation types and final graphic rendering of maps.

Disclosure statement

No potential conflict of interest was reported by the authors.

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