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Geo-hydromorphological assessment of Europe's southernmost blanket bogs

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ABSTRACT: Blanket bogs are a globally rare type of ombrotrophic peatland internationally recognized for long-term terrestrial carbon storage, the potential to serve as carbon sinks, habitat provision and for their palaeoenvironmental archive. This habitat is protected in the European Union under the Habitats Directive (92/43/EEC), but a number of blanket bogs located in the Cantabrian Mountains (northern Spain), representing the southernmost known edge-of-range for this habitat in Europe, are currently not recognized and are at increased threat of loss.

Using climatic data, topography, aerial photography and peat depth surveys, this study has identified 10 new areas of blanket bog located between the administrative regions of Cantabria and Castilla y León. Peat depth data and topography were used to provide a detailed geomorphological description and hydromorphological classification (mesotope units) of these currently unrecognized areas of blanket bog.

Maximum peat depth measured across the 10 sites ranged from 1.61 to 3.78 m, covering a total area of 18.6 ha of blanket bog (>40 cm peat depth). The volume of peat accumulated across the sites was determined to be more than 216 000 m^3 and is estimated to hold 19.89 ± 3.51 kt C. Twenty-four individual hydrological mesotope units were described, indicating a diverse assemblage of blanket bogs in this region.

The peatlands identified in this research extend the known limit of blanket bogs in Europe farther south than previously recorded and – combined with four other unprotected blanket bogs recently identified in the Cantabrian Mountains – these peatlands represent 10.5% of blanket bog currently recognized and protected in Spain. The range of anthropogenic pressures currently acting on peatlands in the Cantabrian Mountains indicates that without protection these important landforms and stored carbon may be lost. An urgent update of European peatland inventories is thus required to preserve these valuable carbon stores and potential carbon sinks. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: peat depth; mesotope; blanket mire; raised bog; peatland; hydromorphological classification; carbon; Spain; windfarms

Introduction

Peat-forming ecosystems (mires) develop in environments where the decomposition of plant and organic matter is inhibited, primarily as a result of anoxic conditions caused by surface waterlogging (Sjörs, 1948; Gorham, 1953; Moore and Bellamy, 1974). Peatlands are generally recognized as ecosystems where more than 30 cm of peat has accumulated (Kivinen, 1980), although it varies between countries; for example, the minimum peat depth required in Ireland is 40 ThinSpace;cm (Cruickshank and Tomlinson, 1990; Evans and Warburton, 2007) and 50 cm in Scotland (Bibby, 1984). In contrast with the definition of 'mires', peatlands may no longer carry peat-forming vegetation (Kivinen, 1980; Immirzi *et al.*, 1992; Charman, 2002; Joosten *et al.*, 2017).

Peatlands accumulate carbon over millennial timescales (Yu *et al.*, 2010), and despite only covering 2.8% (4.2 million km^2) of the Earth's land surface (Xu *et al.*, 2018), these environments are the largest store of terrestrial carbon (Limpens *et al.*, 2008) and play an important role in the global carbon cycle (Gorham, 1991; Yu *et al.*, 2010). However, an estimated 650000 km^2 of known peatlands are reported as damaged or degraded, and release 5–6% of global greenhouse gases, including CO_2, CH_4 and N_2O (Joosten, 2009). In this condition peatlands could act as carbon sources (Parish *et al.*, 2008), but when restored they have the capacity to re-establish a function as carbon sinks (Nugent *et al.*, 2018). The protection, restoration and conservation of peatland environments is, therefore, a key action in helping to mitigate climate change (Joosten *et al.*, 2017).

Various peatland classification systems have been adopted across different countries, and although some early classifications were based on the economic value of the peatland for the exploitation of peat as a resource (Joosten *et al.*, 2017), more recent classifications account for the formation and functioning of the ecosystems through hydrological processes and geomorphology. There is long-standing agreement on the trophic status of peatlands relating to their current source of water supply (Lindsay, 2016a); bogs are ombrotrophic peatlands, receiving water mostly from precipitation (>80%), and are therefore generally acidic (pH<4.6), nutrient-poor environments, while fens are minerotrophic peatlands that receive additional contribution and nutrients from ground water and/or surface runoff, and are generally more base-rich (pH> 5.8) environments (Sjörs, 1950; Gorham, 1985). Transitional peatlands describe the inevitable continuum of ecosystems that exist between ombrotrophic and minerotrophic peatland environments (Gorham and Janssens, 1992).

Further categorization of peatland environments defined landforms based on geomorphology (Weber, 1903), and hydromorphic classification combines geomorphology and hydrology (Dau, 1823; Lindsay, 2016b; Joosten *et al.*, 2017). This latter classification provides two main groups of ombrotrophic bogs – raised bogs and blanket bogs – but also describes a range of minerotrophic peatlands. As peat accumulates, the morphology of the peatland may no longer reflect that of the underlying landform, and thus the source of water supply may change (Lindsay, 2016c). Peatlands that form in depressions or from in-filling lakes can, over time, accumulate such an amount of peat that the central portion becomes raised above the surrounding land, and the system moves from a minerotrophic fen to an ombrotrophic 'raised' bog (Lindsay, 1995). Blanket bogs form a continuous mantle of peat that can cover entire landscapes and are distinctive from raised bogs as the morphology of the 'blanket' of peat is determined largely by the topography of the underlying landform (Lindsay, 1995). Blanket bogs typically form in environments with high precipitation (>1000 mm year^{-1}) and high atmospheric moisture, where mean temperatures are <15 °C with low seasonal variability (Lindsay *et al.*, 1988). Known examples of these globally rare ecosystems (blanket bogs) are predominantly located in areas with oceanic climates above 40° latitude in Northern and Southern Hemispheres (Figure 1).

While entire landscapes covered in peat are often referred to as blanket bog, the mantle of peat invariably comprises a range of bog, fen and transitional mire components based on their topographical location and water supply. Hierarchical classification (Ivanov, 1981; Lindsay, 2016c) provides the most encompassing approach to classifying peatlands, in particular blanket bogs, by combining hydrology, geomorphology and vegetation at different scales to classify components and features of these landscapes, which should perhaps more appropriately be termed blanket mire or blanket peatland. Within such mire complexes, this 'tope system' classification identifies assemblages of hydrologically linked mire/peatland units (macrotopes), individual hydrological units (mesotopes; Figure 2), surface patterns such as pool systems (microtopes), individual features such as pools or hummocks (nanotopes) and the distribution of vegetation within surface structures (Lindsay, 2016c).

Blanket and raised bogs are recognized and protected in the European Union (EU) under the Habitats Directive (92/43/EEC), although bogs and fens currently have the highest proportion of habitat assessed as 'unfavourable – bad' (European Topic Centre on Biological Diversity, 2009) and for Spain this is 'unfavourable – inadequate' (European Comission, 2012). Known Spanish peatlands represent a small proportion of the total land surface of the country (0.07%; Tanneberger *et al.*, 2017), although the inventory of peatland in Spain is incomplete (Heras and Infante, 2018; Chico *et al.*, 2019a). The majority of recognized and protected blanket bogs in Spain are located in Galicia and Asturias (Table I; European Environment Agency, 2019), with one additional blanket bog designated between the Basque Country (Zalama; Heras, 2002) and Castilla y León (Montes de Valnera; European Environment Agency, 2019). However, the majority of the areas recognized as blanket bog in Asturias under the Natura 2000 network are not located in areas with climate or topography suitable for blanket bog development, and the most recent peatland research inventory does not recognize blanket bogs in this region (Pontevedra-Pombal *et al.*, 2017). In addition, the LIFE + Tremedal project only identified one blanket bog in the region, suggesting that the total area of blanket bog in Asturias may only be 16.98 ha (Ramil-Rego *et al.*, 2017). This is clearly an issue in urgent need of further investigation and resolution.

Four currently unrecognized and unprotected blanket bogs have recently been mapped on the boundary between the administrative regions of Cantabria and Castilla y León in the Cantabrian Mountains (Table I , Figure 3; Chico *et al.*, 2019a), and further blanket bogs are considered to exist along this section of the mountain chain (Heras *et al.*, 2017; Chico *et al.*, 2019a). These blanket bogs represent the current southernmost edge-of-range of this habitat in Europe (Chico *et al.*, 2019a), but without designated protection there is little to prevent degradation or loss of these globally important peatlands from anthropogenic pressures.

Historically, domestic peat cutting may have been common in these regions for local use (Heras, 2002), but contemporary

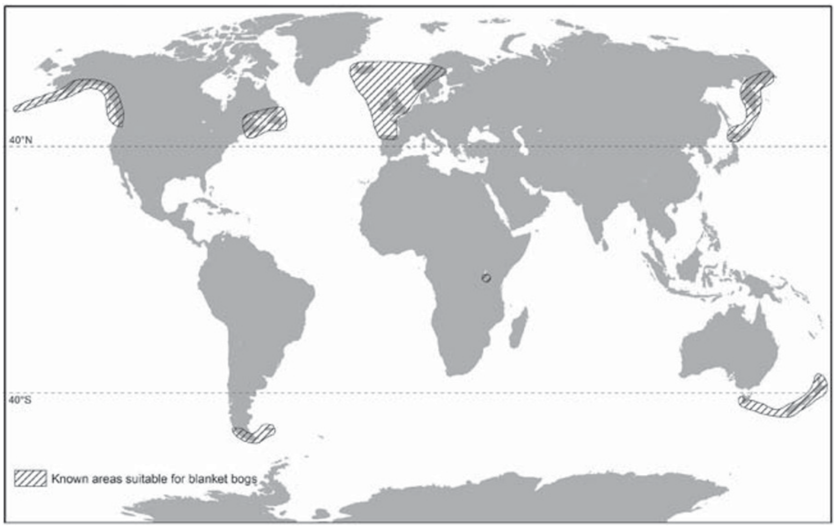

Figure 1. Areas where blanket bogs have been reported (adapted from Lindsay *et al.*, 1988).

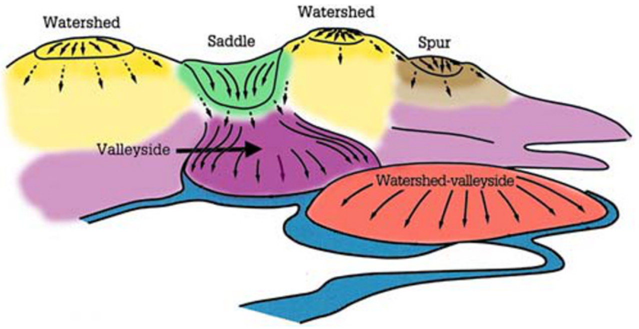

Figure 2. Graphical representation of blanket bog mesotope units (from Lindsay, 2016c). [Colour figure can be viewed at wileyonlinelibrary.com]

anthropogenic pressures on peatlands in northern Spain come from livestock (Chico *et al.*, 2019b), vegetation burning (Heras, 2002), commercial peat extraction (Guerrero, 1987; Heras *et al.*, 2017) and windfarm infrastructure (Heras and Infante, 2008; Chico *et al.*, 2019a). Aeolian and fluvial weathering are important natural drivers of erosion for exposed peat surfaces (Warburton, 2003), but where livestock graze on blanket bog the rate of erosion and peat loss is four to six times greater and over a period of 2 months the rate of peat loss from unprotected blanket bog in Cantabria was shown to be equal to annual mean rates of peat erosion in the UK (Chico *et al.*, 2019b). Additionally, over the last decade, 429 kt of peat has been extracted commercially in Spain (Heras *et al.*, 2017) and some peatlands, such as Tornos blanket bog in Cantabria and Saldropo raised bog in the Basque Country, have been completely removed as a consequence of this extraction activity (Heras and Infante, 2008). Commercial peat extraction is still undertaken in Galicia from some of the best (and protected) examples of Spanish blanket bog. Peat is also extracted and removed to create the foundations for wind turbines, but the infrastructure of tracks associated with windfarms that cross blanket bog units also adversely impacts hydrologic functions by dividing hydrological mesotope units (Wawrzyczek *et al.*, 2018) and altering the endemic peat-forming vegetation (Fraga *et al.*, 2008). Loss of peat as a result of track construction and associated drainage (Lindsay, 2016c) may also be significant for the small edge-of-range blanket bogs in the Cantabrian Mountains (Chico *et al.*, 2019a).

Although protected areas of blanket bog in Spain are still under pressure, EU funding is available to enable restoration and conservation of these ecosystems, as demonstrated by the interventions undertaken at Zalama blanket bog (Heras and Infante, 2018; Chico and Clutterbuck, 2019). Currently unrecognized and thus unprotected areas of blanket bog are, however, under greater threat. This study aims to: (1) extend the identification of unmapped blanket bogs lying along the boundary between Cantabria and Castilla y León administrative regions in the Cantabrian Mountains; (2) undertake geomorphological

Table I. The extent of blanket bog in Spain recorded under the Natura 2000 network (European Environment Agency, 2019) together with currently unprotected areas (Chico *et al.*, 2019a). *The area of blanket bog reported in Asturias under Natura is thought to be an overestimate due to incorrect classification (Ramil-Rego *et al.,* 2017).

	Region	Area (ha)
		2499.5
	Asturias	*16.98**
	Galicia	373.4
	Castilla y León	14.61
Protected	Basque Country	4.41
	Cantabria	12.50
Not currently protected	Castilla y León	11.77

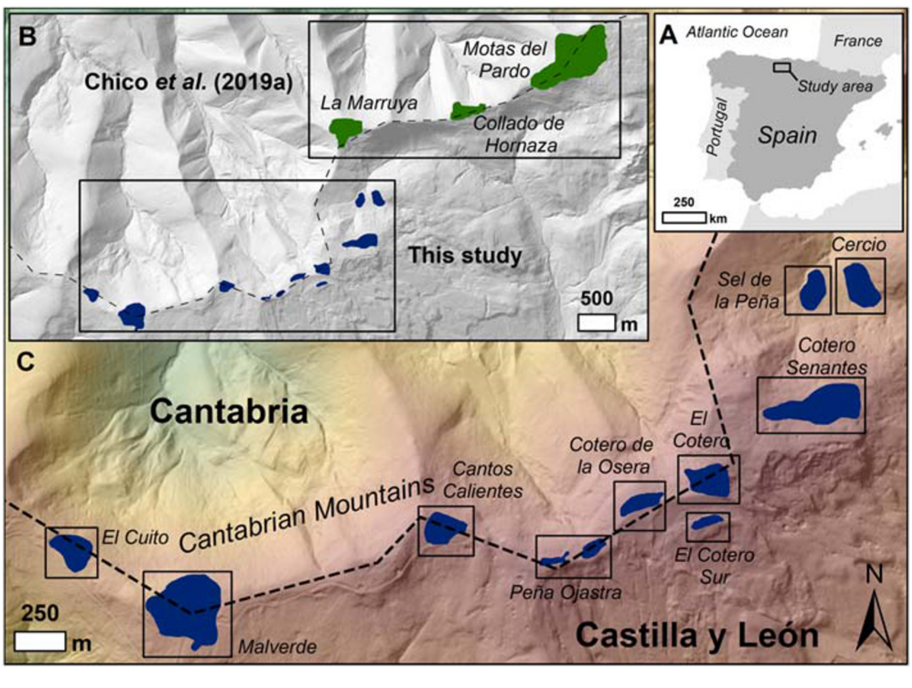

Figure 3. Location of study areas (A and C) and blanket bogs mapped by Chico *et al.* (2019a) (B) in the Cantabrian Mountains, north Spain. [Colour figure can be viewed at wileyonlinelibrary.com]

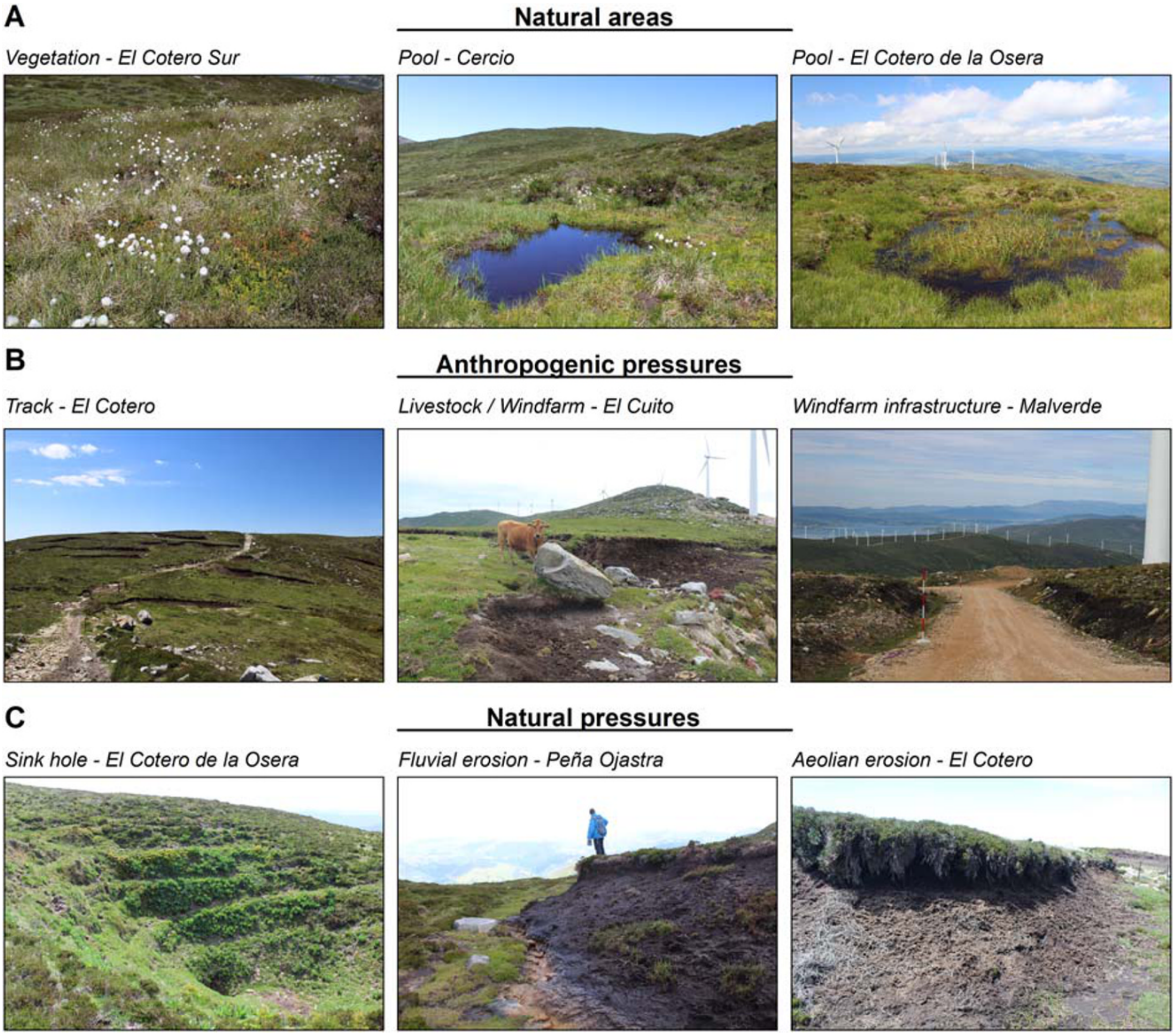

Figure 4. Examples of natural (mire/peatland) areas (A), and anthropogenic (B) or natural pressures (C) within the study sites. (Image titles: *Description of image content – Site name*). [Colour figure can be viewed at wileyonlinelibrary.com]

assessment (including estimation of carbon stored) and hydromorphological classification of any peatland systems found; (3) provide information to update the inventory of peatlands in Europe; and (4) facilitate promotion of designation, restoration and protection of any peatland systems identified.

Methods

Study area

The geographical area covered in this study focuses on the boundary between the administrative regions of Cantabria and Castilla y León in the Cantabrian Mountains (Figure 3) and extends a previous survey (Figure 3B; Chico *et al.*, 2019a) along the mountain ridge between the Estacas de Trueba and Escudo mountain passes. The study area ranges in elevation from 1200 to 1500 m above sea level (m asl) and predominantly comprises mountain summits with some ridge and valleyside areas. This section of the mountain range is characterized by sandstone and limestone (Cantabria Government, 2019), with sinkholes indicating the presence of a karst landscape in some areas (Figure 4C). The climate is suitable for blanket bog development, with annual mean temperatures of 7.6 °C and total precipitation of >1600 mm year^{-1} reported at Zalama, 30 km northeast along the mountain chain (Heras, 1990). Occult precipitation from low cloud and fog is also consistent during the year (Heras and Infante, 2003).

Areas of potential blanket bog were identified for ground survey using local climate data, topographic location and the presence of erosion features or pools visible in aerial photography following the protocol developed by Chico *et al.* (2019a). Climatic variables were obtained from the global climate data model WorldClim (Hijmans *et al.*, 2005), digital elevation models (DEMs) at 0.25 m resolution were sourced from the Spanish National Geographical Institute (Instituto Geográfico Nacional, 2019) and ortho-corrected colour (RGB) aerial photographs for 2017 were acquired from Mapas Cantabria (Cantabria Government, 2019).

Ten potential areas of blanket bog were identified at El Cuito, Malverde, Cantos Calientes, Peña Ojastra, Cotero de la Osera, El Cotero, El Cotero Sur, Cotero Senantes, Cercio and Sel de la Peña (Figure 3C). Peat-forming species such as hare's-tail cottongrass (*Eriophorum vaginatum*), common cottongrass (*Eriophorum angustifolium*) and *Sphagnum* spp. were present at all sites within a more diverse vegetation including heather (*Calluna vulgaris*), cross-leaved heath (*Erica tetralix*) and bilberry (*Vaccinium myrtillus*) (Figure 4A).

Peatland characteristics

Peat depth, volume and peatland extent

The initial survey area for each site was identified using the presence of erosion features or pools visible in aerial photographs. These, and natural boundaries such as cliffs and rock outcrops if present, were used to estimate the initial extent of the peatlands. A systematic 15 msquare grid of points was created for each site and surveyed in July 2019. Each survey point was located using a Garmin GPSMAP64 handheld GNSS reporting an accuracy of ±3 m. Peat depth was measured using connectable 50 cmlength sections of steel rod (6 mm in diameter), and additional 15 m survey point locations were added where peat depth greater than 30 cm was recorded at the initially estimated edge of the survey area. A peat core was collected from one location at Malverde blanket bog using a 5 cmdiameter semi-cylindrical Russian peat auger. Peat depth determined using the auger at Malverde, and also at five locations in Chico *et al.* (2019a), was typically within 2–4 cm of the depth estimated using a rod prior to core extraction. In this area, peatlands usually lie over the bedrock with very little or no clay layer (Heras, 2002).

Peat depth measurements for each site were interpolated to create a map of the peatland using a spline algorithm in ArcGIS 10.3.1, and the main body of peatland was delimited using a minimum peat depth of 40 cm (Cruickshank and Tomlinson, 1990). The peatland margins were identified as areas where peat depth ranged from 30 to 40 cm, and the volume of peat at each site was determined from all interpolated peat depth values. Any correlation between the extent of each blanket bog and both maximum peat depth measured and mean interpolated peat depth were assessed using Pearson's coefficient in R (v3.6.2).

Organic carbon content

The organic carbon content of the peat core from Malverde was determined using the loss on ignition (LOI) method (Agus *et al.*, 2011). The peat core was analysed in 5 cm sections along the entire length. Samples were dried in an oven at 105 °C for 24 h or until a consistent dry weight was achieved (M_s). The dry samples were subsequently burned at 550 °C for 6 h to remove organic matter (leaving M_{ash}). The volume of each sample was determined from the dimensions of the auger and used to calculate the dry bulk density (*BD*):

$$BD = \left\{\frac{M_s}{V}\right\} \tag{1}$$

where M_s is the dry mass of the peat sample (g) and V is the volume of the sample (cm^3).

The organic carbon content (C_{org}) of the organic matter and the weight of organic carbon per unit volume of peat (C_v) were then estimated using the generalized relationship between organic matter and carbon content (Agus *et al.*, 2011):

$$C_{org} = \left\{\frac{M_s - M_{ash}}{M_s}\right\}/1.724 \tag{2}$$

where C_{org} is the organic carbon content of the organic matter (%), M_s is the dry mass of the peat sample (g) and M_{ash} is the mass of the sample remaining (ash) after LOI (g);

$$C_v = BD * C_{org} \tag{3}$$

where C_v is the weight of organic carbon per unit volume of peat (g cm^{-3}).

The mean weight of organic carbon per unit volume of peat determined for the peat core and the volume of peat estimated from interpolations were used to estimate the carbon stored in each blanket bog.

Landscape analysis

Slope and aspect

Slope (in degrees) and aspect (classified in eight directions) for the extent of each peatland identified were determined from the DEMs at 0.25 m resolution using the surface analysis tools in ArcGIS 10.3.1.

Exposed peat

Areas of exposed peat were digitized from the 2017 aerial photographs. Any potential correlation between the area of exposed peat and the extent of each peatland was explored using Spearman's rank correlation in R (v3.6.2). The standardized area of exposed peat per unit area of each blanket bog was also determined for subsequent analysis.

Hydromorphological analysis (mesotopes)

Surface water flow paths for each site were determined from the DEM for 2017 using the hydrology tools in ArcGIS 10.3.1. Individual mesotope units were identified and mapped for each site from the hydrological flow patterns and peat depth (Ivanov, 1981; Lindsay, 2010; Chico *et al.*, 2019a). The mean interpolated peat depth, maximum measured peat depth, mesotope extent and area of exposed peat were determined for each individual mesotope. A generalized linear model (GLM) was performed to identify whether peat accumulation or current levels of erosion are influenced by mesotope type.

Results

Peatland characteristics

Peat depth, volume and peatland extent

A total of 1499 peat depth measurements were taken across the extent of all study sites. The maximum recorded peat depth ranged from 1.61 m at El Cuito to 3.78 m at Malverde (Table II; Figure 5). Sinkholes at Peña Ojastra and El Cotero de la Osera, and rock outcrops at all sites, limit the extent of the peatlands and in most cases act as part of the peatland margin (Figures 4C and 5). The combined area of blanket bog with peat depth greater than 40 cm covers 18.64 ha, increasing to 21.76 ha if the peatland margin (peat depth >30 cm) is included (Table II). The total volume of peat accumulated across all sites is greater than 216 000 m^3 (Table II). The area of blanket bog was correlated with maximum peat depth recorded (r = 0.87, p = 0.001), but did not correlate with mean peat depth for each site (r = 0.55, p = 0.099).

Carbon stored

The peat core measured 294 cm and provided 59 peat samples for the measurement of organic carbon content. The carbon content and bulk density measurements indicate a clear difference in the composition of the peat in the main peat body compared to the peat in the basal layer (Figure 6). The section of the core representing the main peat body extends from the peat surface to approximately 271 cm depth. In this section the carbon content ranged from 52 to 57.5%, showing a general increase with depth (Figure 6). The section of the core representing the peatland base (estimated to be at around 281–294 cm depth) contained far lower carbon content, ranging from 4.7 to 7.5% (Figure 6). In a transitional section of the core between 271 and 281 cm, the carbon content decreased by over 80%, from 53 to 7.5% over just 10 cm depth of peat.

Table II. Landscape and peatland characteristics by study area.

	Study site	El Cuito	Malverde	Cantos Calientes	Peña Ojastra	Cotero de la Osera	El Cotero Sur	El Cotero	Cotero Senantes	Cercio	Sel de la Peña
Survey area (ha)		2.56	9.45	2.31	1.32	1.39	0.77	2.71	6.14	3.25	2.21
Number of survey points		115	489	104	62	63	37	121	277	129	102
	Altitude (m asl)	1228	1325	1427	1452	1492	1481	1474	1413	1271	1246
	Location (°)	43.0813 −3.7989	43.0782 −3.7887	43.0807 −3.7781	43.0809 −3.7657	43.0832 −3.7628	43.0824 −3.7580	43.0840 −3.7577	43.0854 −3.7490	43.0923 −3.7489	43.0931 -3.7522
	Mean ± SD slope (°)	12.6 ±9.7	14.3 ±9.8	14.9 ±11.8	14.3 ±9.9	12.8 ±7.7	12 ±8.8	14.7 ±7.7	13.7 ±8.3	14.9 ±8.4	18.8 ±10.6
Landscape characteristics	Dominant aspect	N	N	S	NW	NW	N	N	NE	SW	N
	Area of exposed peat (m^2)	939.3	1782.9	883.2	383.2	301.3	83.4	669.6	1249.5	529.7	193.2
	Standardized area of exposed peat (m^2 ha^{-1})	502.3	471.7	496.2	197.5	146.3	44.6	315.8	505.87	195.5	112.3
	Maximum peat depth (m)	1.61	3.78	1.78	1.97	2.06	1.87	2.12	2.47	2.71	1.72
	Mean ± SD peat depth (m)	0.71 ±0.43	0.84 ±0.93	0.63 ±0.41	0.35 ±0.18	0.69 ±0.47	0.68 ±0.52	0.58 ±0.47	0.64 ±0.52	0.75 ±0.53	0.66 ±0.43
	Peat extent (ha; >40cm depth)	1.67	5.94	1.01	0.56	0.91	0.43	1.41	3.47	2.00	1.24
	Peat extent (ha; >30cm depth)	1.87	6.49	1.29	0.74	1.08	0.54	1.76	4.26	2.26	1.47
	Peat volume (m^3)	15657	91262	9903	5559	8732	4273	13671	34414	20624	11908
Peatland characteristics	Carbon content ± SD (kt)	1.44 ±0.26	8.41 ±1.54	0.91 ±0.17	0.51 ±0.09	0.80 ±0.15	0.39 ±0.07	1.26 ±0.23	3.17 ±0.58	1.90 ±0.35	1.10 ±0.20

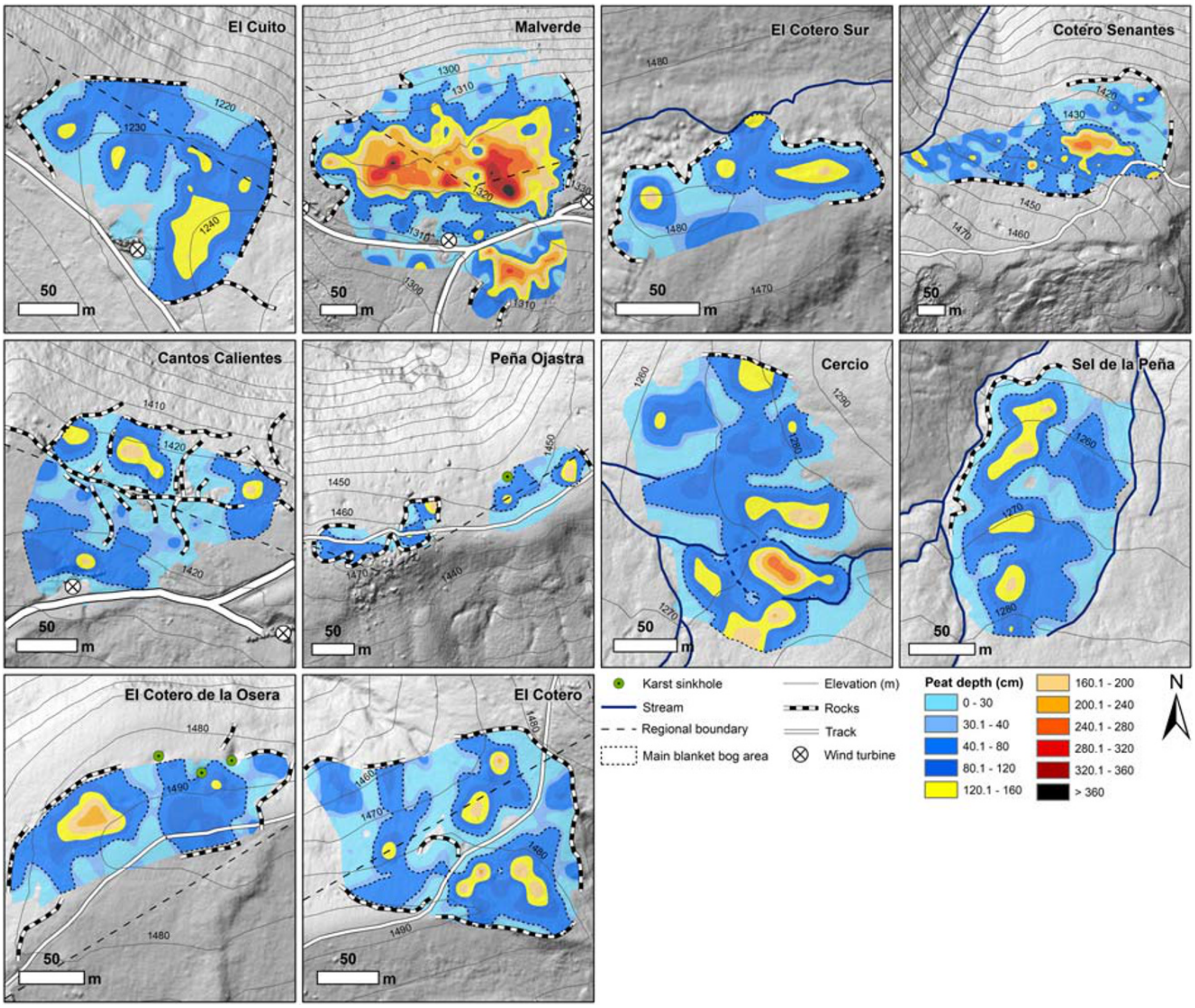

Figure 5. Peat depth and extent of main blanket bog areas in each study site. [Colour figure can be viewed at wileyonlinelibrary.com]

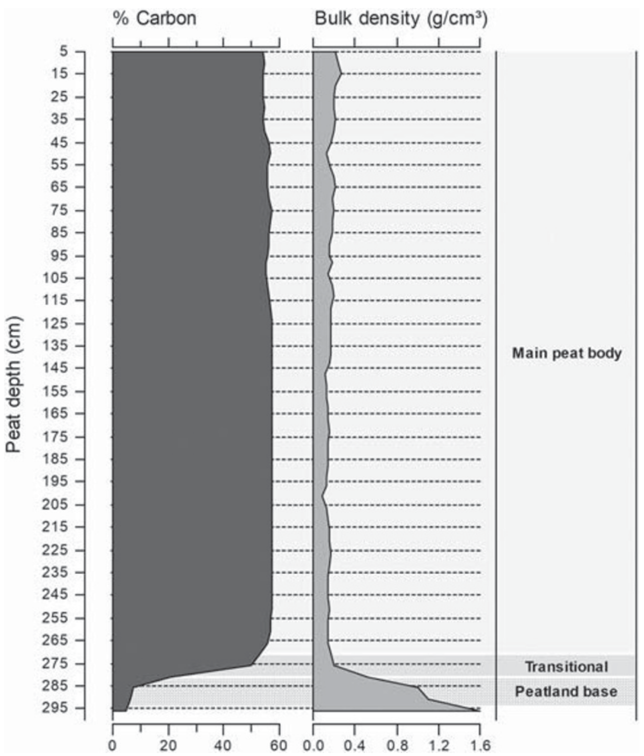

Figure 6. Carbon content (%) and bulk density (g cm^{-3}) for the peat core collected from Malverde blanket bog.

The bulk density of the dry matter determined for the whole peat core was 0.22 g cm^{-3}, but there is notable variation with depth. In the section of the core representing the main peat body, *BD* values showed a general decrease from a maximum of 0.26 g cm^{-3} in the top 15 cm to a minimum of 0.08 g cm^{-3} at 201.5 cm depth (Figure 6). A progressive increase in *BD* from 0.19 to 1.59 g cm^{-3} is evident through the transitional and peatland base sections (Figure 6).

The peat in the core was determined to contain 92.08 ± 16.89 kg C m^{-3}. The blanket bogs mapped in this study are vestimated to contain 19.9 ± 3.51 kt C (Table 2).

Landscape analysis

Slope and aspect

For eight of the peatlands assessed, the majority of the peat has accumulated on north-facing slopes (ranging typically from NW to NE). The main body of peat in two of the peatlands (Cantos Calientes and Cercio) appears to have accumulated on more southwest-facing slopes (ranging from S to W).

The mean slope of the majority of the peatland surfaces ranges from 12 to 15°, although a higher angle of 18.8° was determined for Sel de la Peña (Table 2).

Exposed peat

Multiple areas of exposed peat were present in all study areas (Figure 7). There was a strong positive correlation between

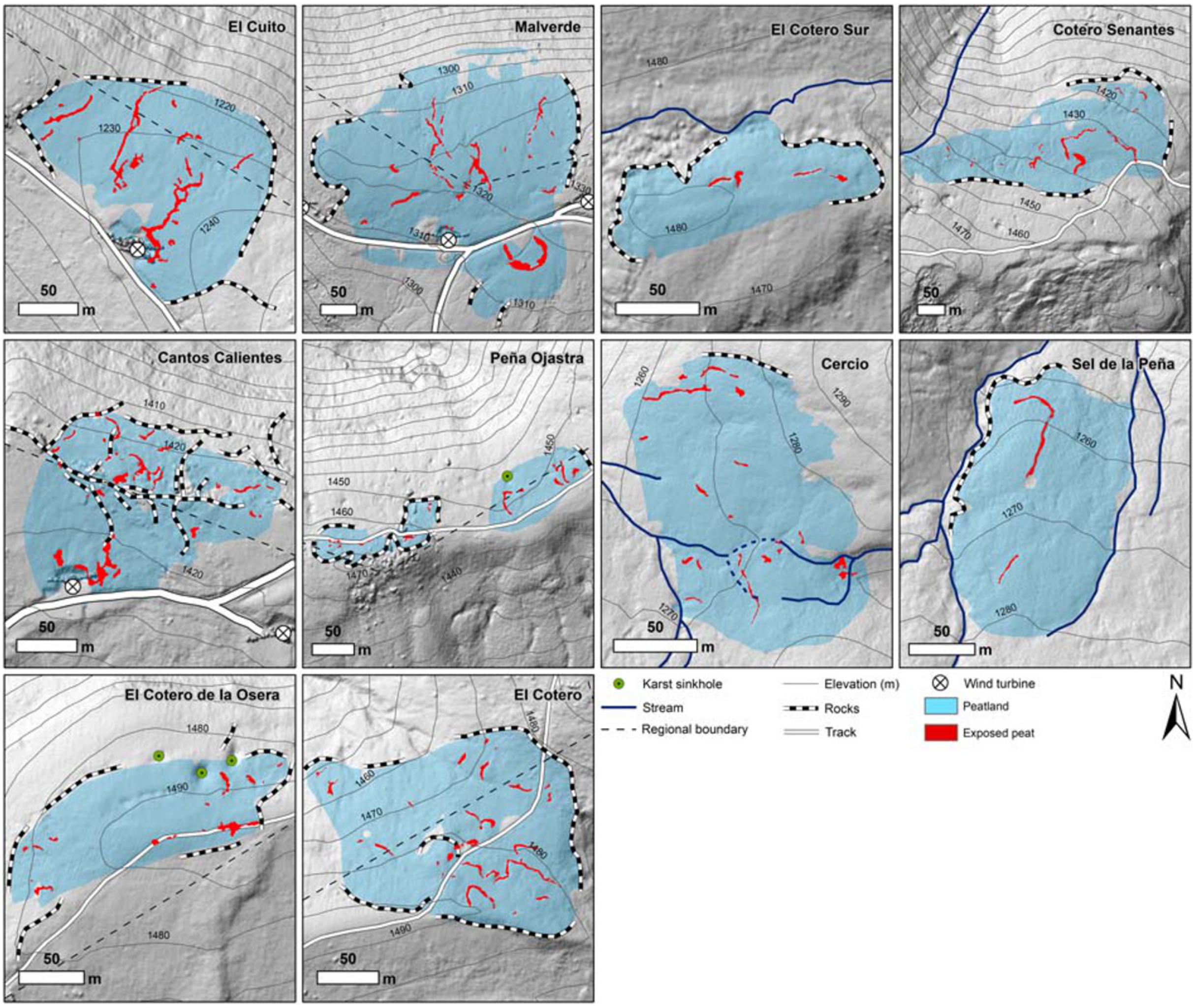

Figure 7. Areas of exposed peat present in the study areas. [Colour figure can be viewed at wileyonlinelibrary.com]

the extent of the peatland and the total area of exposed peat ($S = 32$, $p = 0.008$).

Hydromorphological assessment

Across the 10 sites surveyed, 23 blanket bog mesotopes were identified. The most common units identified were valleyside mesotopes (11 units) occurring at five of the sites, with up to three individual units per site when present (Table III). All other mesotope types, where observed, were only found to occur once at each site: watershed mesotopes (7 units); spur mesotopes (3 units); saddle mire (2 units). Fen ecosystems that were hydrologically connected to the mapped blanket bog mesotopes were only identified at four of the sites, but further surveying is required to define the presence and extent of these fen areas.

Variation between mean interpolated peat depth measurements and mesotope type was evident (Figure 8), although the highest mean interpolated peat depth recorded across watershed mesotopes (78.9 cm, Figure 8) was only 30 cm greater than the mean interpolated peat depth recorded across saddle mire units (49.3 cm, Figure 6). The maximum peat depth recorded for each mesotope type varied across all sites, with no indication that any particular mesotope type displayed a tendency to accumulate deeper peat (Table 3). The two highest measurements of peat depth were both recorded at one site (Malverde) in a spur mesotope (378 cm) and a watershed mesotope (372.5 cm). Both of these measurements are over 125 cm greater than any other maximum depth measured across all sites (Table 3). The GLM did not identify any influence of mesotope type on peat depth.

At Cercio, a domed bog unit surrounded by fen units within the wider blanket mire complex was classified as a raised bog, though it has characteristics intermediate between saddle raised bog and a blanket bog saddle mire mesotope (Figure 9). The peat depth measurements recorded in this mesotope indicate that the peat accumulation fills a depression and as the domed surface (the raised bog unit) is currently higher than the surrounding fen units (Figure 9), the bog is an independent hydrological unit. The mean interpolated peat depth in this bog unit (149.2 cm) was higher than the mean interpolated peat depth determined in any more distinct blanket bog mesotope.

The majority of the mesotope units are bordered by natural geomorphological features, including rock ridges (e.g. El Cuito and Malverde; Figures 4 and 9), rock outcrops (e.g. Cantos Calientes and Cotero Sur; Figure 9) and karst sinkholes (e.g. El Cotero de la Osera; Figures 4 and 9). These features act as the geo-hydromorphological limit or edge of the peatland, but anthropogenic pressures have changed the geomorphology of all the landforms to varying degrees. Vehicle access tracks for the windfarms at El Cuito, Malverde and Cantos Calientes, and farm tracks at Peña Ojastra, El Cotero de la Osera and El Cotero (e.g. Malverde and El Cotero; Figure 4B) provide clear evidence of disturbance. Visible trampling by livestock was also evident in the erosion features found at all peatlands (e.g. El Cuito; Figures 4B and 7). The GLM did not identify that mesotope type influenced the level of erosion.

Table III. Mean interpolated, maximum measured peat depth and exposed peat by mesotope type at study sites

Site	Mesotope	Mean interpolated peat depth (cm)	Maximum measured peat depth (cm)	Mesotope extent (ha)	Exposed peat (m^2)	Standardized exposed peat (m^2 ha^{-1})
Cantos Calientes	Watershed	75.4	178	0.24	68.8	286.7
El Cotero de la Osera	Watershed	64.5	206	1.46	301.3	206.4
Cotero Senantes	Watershed	106.9	247	1.13	703.4	622.5
Cotero Sur	Watershed	58.6	187	0.74	83.4	112.7
El Cuito	Watershed	78.8	161	1.24	489.8	395.0
Malverde	Watershed	112.8	372.5	3.60	613.8	170.5
Peña Ojastra	Watershed	55.5	90	0.18	47.4	236.3
El Cuito	Spur	51.5	151.5	1.17	445.5	380.8
Malverde	Spur	93.8	378	3.08	461.1	149.7
Peña Ojastra	Spur	43.3	160	0.14	60.2	430.0
Sel de la Peña	Spur	59.3	172	1.99	193.2	97.1
El Cotero	Saddle	59.5	211.5	1.59	547.4	344.3
Peña Ojastra	Saddle	39.1	196.5	0.73	267.8	366.8
Cantos Calientes	Valleyside	94.1	172	0.21	207.6	988.6
Cantos Calientes	Valleyside	52.3	176	0.73	277.5	380.1
Cantos Calientes	Valleyside	76.4	146.5	0.13	35.2	270.8
Cercio	Valleyside	61.0	200	1.95	268.8	137.8
Cercio	Valleyside	96.0	136	0.05	11.0	220.0
Cercio	Valleyside	99.8	203.5	0.40	62.8	157.0
Cotero Senantes	Valleyside	37.8	140	1.00	111.9	111.9
Cotero Senantes	Valleyside	57.9	244	1.61	367.9	228.5
Cotero Senantes	Valleyside	55.8	174	1.18	47.6	40.3
El Cotero	Valleyside	42.8	163	0.95	96.4	101.5
Malverde	Valleyside	66.2	288.5	1.04	588.5	565.9
Cercio	Raised bog	149.2	270.5	0.19	55.8	293.7

Discussion

Extending the work presented in Chico *et al.* (2019a), this study has identified and mapped 10 further areas of currently unrecognized blanket bog in northern Spain and classified these to mesotope level. The location of these blanket bogs extends the reported edge-of-range of this habitat in Europe (Heras *et al.*, 2017; Chico *et al.*, 2019a), 2.5 km farther south, and the maximum peat depth recorded at Malverde (3.78 m) is the greatest value of peat depth recorded for a blanket bog in the Cantabrian Mountains (1 m more than the greatest peat depth recorded at Zalama; Chico *et al.*, 2019a). The blanket bog identified at Cotero de la Osera is also the highest blanket bog currently recorded in Spain (1491 m asl), located at an elevation 161 m greater than Zalama blanket bog (Heras and Infante, 2003). Although the best studied and largest examples of blanket bog in Spain are located in Galicia (Heras *et al.*, 2017), the number and diversity of blanket bog hydromorphological units (mesotopes) that have now been identified between Cantabria and Castilla y León regions highlights the importance of this region of the Cantabrian Mountains for globally rare and important blanket bog habitat and more particularly, for the distribution of the habitat '7130 – Blanket bog' in Europe.

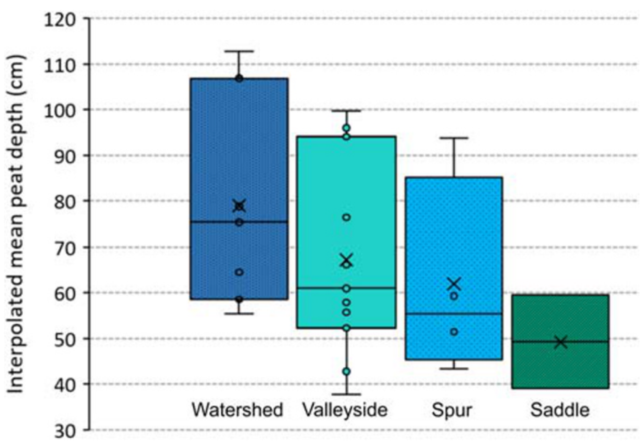

Figure 8. Mean interpolated peat depth recorded by blanket bog mesotope type at the study sites. [Colour figure can be viewed at wileyonlinelibrary.com]

Although the maximum peat depth recorded in this study correlated with the extent of blanket bog – the largest expanses of peat having the greatest values for maximum depth – it is important to note that the mean interpolated peat depths did not correlate with extent (p = 0.099). This suggests that the functioning of a blanket bog ecosystem in terms of its capacity to capture and store carbon is not constrained by size. Furthermore, although these areas of blanket bog are not extensive, their geographical significance outweighs their extent. The combined area of unrecognized blanket bog reported in the present study and that in Chico *et al.* (2019a) is equivalent to 1.5% of all blanket bog recorded in Spain under Natura 2000. However, given that the reported extent of blanket bog reported in Asturias may be a significant overestimate

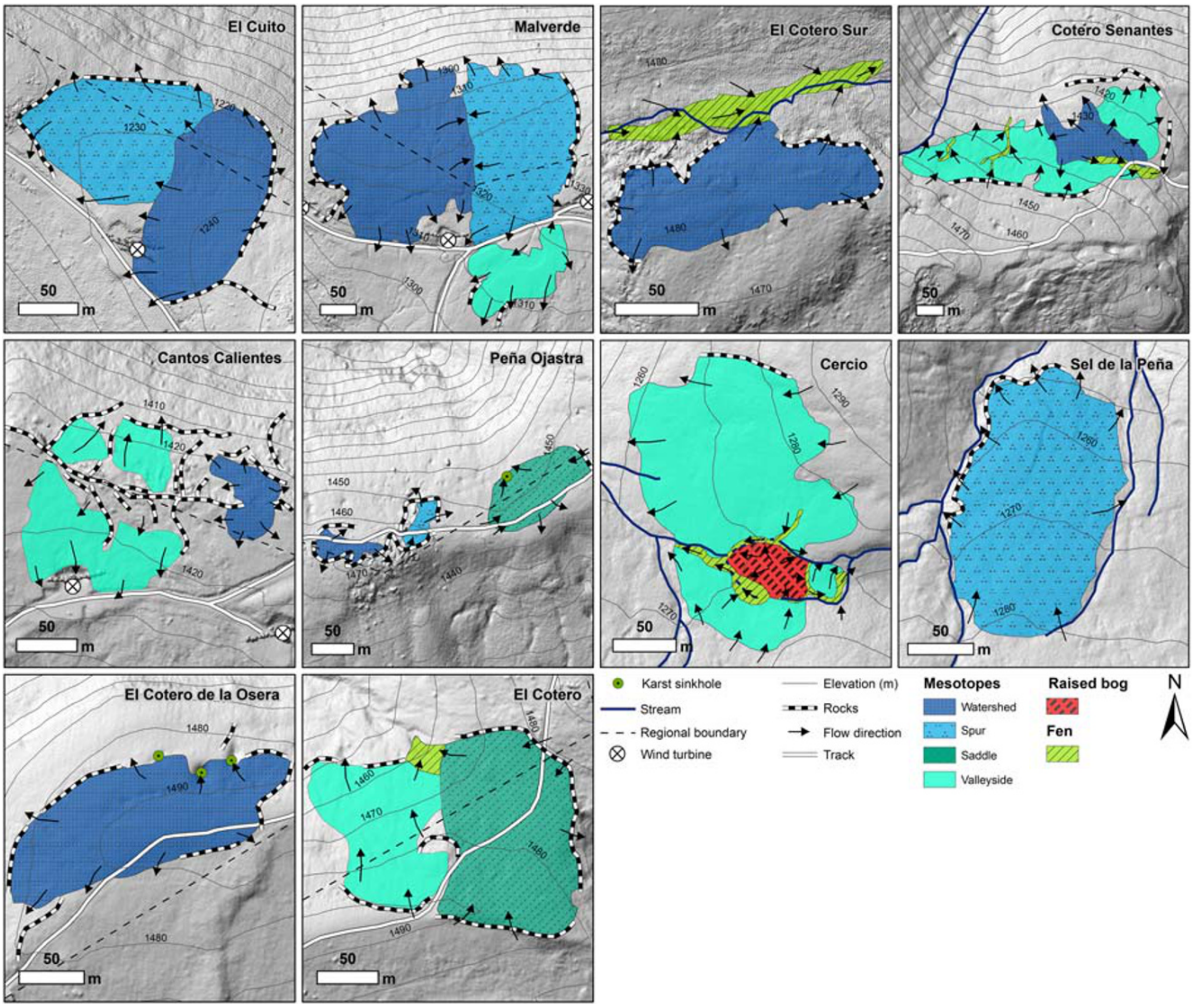

Figure 9. Mesotopes units in each study site. [Colour figure can be viewed at wileyonlinelibrary.com]

(Ramil-Rego *et al.*, 2017), the areas described here and in Chico *et al.* (2019a) may actually represent an additional 10.5% of the resource relative to the area of blanket bog currently recognized under the Habitats Directive in Spain. The climate and topography in the area of the Cantabrian Mountains examined have given rise to a comparatively wide zone of blanket bog development within a part of Europe not generally known for blanket bog habitat. Given their apparent edge-of-range status, but also the evident damage currently occurring across these areas (Figures 4 and 7), there would seem to be a compelling argument for their inclusion in the national and European inventory of peatlands under the Natura 2000 network.

While the purpose of the survey was the identification of blanket bog habitat, measurement of peat depth and classification of hydromorphological mesotopes along this high-level massif, further surveying is required to map and understand the importance of the wider mire complexes, particularly the areas of shallow peat (<30 cm deep) to determine the degree to which such areas contribute to carbon storage. It will also be important to identify and map the interconnections between the ombrotrophic and minerotrophic areas (Figure 9). Rock outcrops and karst sink holes appear to play some part in limiting the extent and development of peatlands in the Cantabrian Mountains. In particular, the sink holes may act as drainage features (Figure 4C), although these may not, of themselves, limit blanket bog formation across adjacent ground. 'Sink holes' are common features within blanket bog landscapes yet show no evidence of preventing peat growth beyond their immediate vicinity (Smart *et al.*, 2013). The GLM did not identify any significant influence of mesotope type on peat accumulation, but this may simply arise from the low number of observations available. Additional data from a wider range of mesotopes across northern Spain are required in order to better assess potential relationships between mesotope type and the variables analysed.

Landscape analysis provides insight into the formation of blanket bogs in this region. It is reasonable to assume that comparable amounts of rainfall, including occult precipitation from low cloud and fog (Heras, 2002), are received across the study area. For 8 of the 10 blanket bogs, the majority of the main peat body lies on north-facing slopes. This preferential aspect of blanket bog development most likely reflects the supply of water from the Atlantic Ocean deposited on the north faces of the primary mountain ridge. The lower frequency of peat accumulation on south-facing slopes may therefore be linked simply with the reduced amount of precipitation (rainfall and occult) that reaches areas south of the ridge. At Cantos Calientes, a third of the main peat body is located on the north side (NW to NE) of the ridge, but almost 50% of the peat extends down the south (SW to SE) slope. This peatland has a greater presence of rock outcrops than any other site in this study, and these outcrops extend from the ridge down the south slope (Figure 5). It is possible that rock outcrops are influential in promoting peat development on south-facing slopes in this region, by capturing and transferring water from the mountain ridge. This process would, however, appear to be less successful than direct precipitation as the maximum peat depth measurements in this peatland were recorded on the north-facing slopes. It is interesting to note that two of the blanket bogs, Sel de la Peña and Cercio, are not located on the primary mountain ridge, but have formed on the next ridge due east. Their presence could be due to a section of the main ridge with a lower elevation than the surrounding summits that allows fog to pass through.

Although small individual pools were noted at most study sites, there was no evidence of a network of pool systems that are typical features of other blanket bogs of Atlantic coasts of Newfoundland in Canada (Price, 1992), Ireland (Hammond, 1978) and Great Britain (Lindsay, 1995). The blanket bogs studied in this region of Spain have formed on relatively high slopes (14–19°; Table II), and this may inhibit pool systems developing. Blanket bogs can form on slopes up to 22° (Tallis, 1973), but on steeper slopes peat becomes unstable (Gorham, 1957), so it is also possible that pool systems were present in these blanket bogs in the past but have been lost due to bog bursts or peat slumping. The blanket bogs in this region of Spain appear comparable with blanket bogs located on the wet mountain peaks of central and eastern areas of Ireland (Hammond, 1978). However, the role of occult precipitation from fog is important for blanket bog development in areas with low precipitation, and in this respect, the drivers of blanket bog development along the Cantabrian Mountains seem comparable with those in Newfoundland (Price, 1992).

The dry bulk density of blanket peat is variable, with values typically ranging from 0.04 to 0.34 $g\,cm^{-3}$ (Chapman *et al.*, 2015). The values of bulk density determined for the peat at Malverde sit clearly in this range, but the general decrease with depth may provide insight to the state or composition of the peat. In pristine or relatively intact *Sphagnum*-rich peats, bulk density is reported to be lower at the surface, increasing with depth (Clymo, 1983; Lindsay, 2010). The peat in this region of Spain may therefore not be *Sphagnum*-rich, or, alternatively, the decrease in bulk density may just highlight that the peat here is degraded (Frogbrook *et al.*, 2009). Further understanding can only be obtained through pollen analysis and carbon dating of the peat. Interestingly, the carbon content determined for the main peat body section of the core from Malverde (52–57.5%) is comparable to that found in blanket bogs located in western European islands such as the United Kingdom and Ireland (Loisel *et al.*, 2014), but higher than the carbon content determined in blanket bogs in the west of Spain (Galicia: 42–51%; Ramil-Rego and Aira-Rodríguez, 1994).

The bog mesotope at Cercio, considered to be intermediate between saddle raised bog and blanket bog saddle mire unit, is surrounded by fen on all sides and forms an unusual component of the larger blanket mire complex and is perhaps a unique type of landform in Spanish blanket bogs; in fact, another raised bog with similar characteristics can be found in Galicia (e.g. Chao de Veiga Mol), although in this case this peatland has been described as an 'intact' raised bog with up to 915 cm of peat (Pontevedra-Pombal *et al.*, 2019). Interpretation of the unit as intermediate form is based on current morphology, but it should be noted that the area is under high anthropogenic pressures, which may have altered the 'natural' morphology and context of this mire system. It is possible that at some time in the past it was connected to, and therefore part of, the larger valleyside mesotope. However, the mean interpolated peat depth in this unit is almost 40 cm greater than the mean interpolated peat depth for any blanket bog mesotope surveyed in this area, thus perhaps indicating different initiation and accumulation processes. Across Europe, raised bogs usually have greater accumulation of peat than blanket bogs (Lindsay, 1995).

Blanket and raised bogs in northern Spain face significant anthropogenic pressures. Although activities such as domestic peat extraction, which may have been important in the past (Heras, 2002; Heras and Infante, 2008), were not visibly occurring in any of the sites studied, livestock are widespread in the Cantabrian Mountains; cattle and horses were observed at all study sites during the course of the field survey. The presence of grazing livestock significantly increases the rate of peat loss from blanket bogs in this region (Chico *et al.*, 2019b), and disturbance from hooves was evident in exposed peat present at each site (Figures 4 and 7). The positive correlation between the extent of the blanket bog and the area of exposed peat indicates that degradation of these landforms is consistent and may be linked more strongly with anthropogenic pressures than with topographical influences. Exclusion of livestock significantly reduces the rate of peat loss in this region (Chico and Clutterbuck, 2019), and this intervention will be required if degradation of these landforms is to be halted and reversed. Such actions could be facilitated by EU funding if these blanket bogs were to be designated under the Natura 2000 network.

Morphological change as a result of peat extraction and grazing is significant in the long term, yet far greater and more rapid change has occurred as a result of windfarm construction. Although the installation of individual turbines over blanket bog often results in the extraction of peat in isolated locations, the associated infrastructure of tracks and electrical cable conduits has wider impact not only on the hydrology, but also on peatland geomorphology (Heras and Infante, 2008; Wawrzyczek *et al.*, 2018). Of the 10 blanket bogs identified in this study, three have wind turbines or infrastructure adjacent to, or inside, the main body of peatland. Windfarm tracks at El Cuito and Cantos Calientes may be impacting on the stability of the peat and the hydrology of the peatland margin. The most significant change as a consequence of track construction is at Malverde, where significant amounts of peat were removed to enable track installation, and the track appears to have divided a large spur mesotope into a spur and valleyside mesotope (Figure 9). In addition, drainage installed along the sides of the track will continue to impact on the hydrology at the edges of these two new mesotopes (Grace *et al.*, 2013; Wawrzyczek *et al.*, 2018).

Furthermore, the removal of peat at Malverde has resulted in a loss of associated long-term carbon storage, and blanket bog vegetation has also been replaced by track material. At Serra do Xistral in Galicia, some endemic vegetation communities have been lost in blanket bogs as a consequence of windfarm installation (Fraga *et al.*, 2008), and although a systematic vegetation survey focusing on *Sphagnum* spp. did not form part of this study, at least three species – including *Sphagnum palustre*, *Sphagnum fallax* and *Sphagnum capillifolium* – were identified in the main body of blanket bog at Malverde. The presence of peat-forming species indicates the potential for blanket bogs in this region to act as carbon sinks, although urgent protection and restoration activities will be needed if this benefit is to be realized. The greatest immediate carbon benefit arising from positive conservation management of these areas, however, lies in the area of 'avoided losses' when it is considered that an area of 1 ha only 30 cm deep contains as much carbon as all the carbon stored in 1 ha of tropical rainforest – yet total loss of 30 cm of peat is much more easily achieved than total loss of a stand of tropical rainforest (Lindsay *et al.*, 2019).

In addition to the ongoing damage observed, the remainder of the blanket bogs presented in this research are under additional threat as further windfarm development has been promoted by a number of energy companies and the Cantabrian

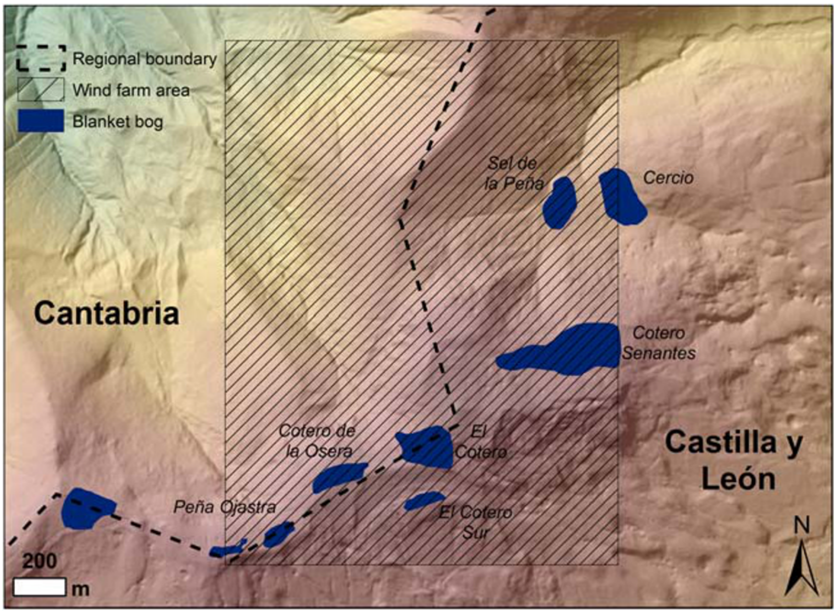

Figure 10. One proposed area for windfarm development (BOE, 2015) on the regional boundary. [Colour figure can be viewed at wileyonlinelibrary.com]

government (BOE, 2015). One proposed area for windfarm installation affects all the blanket bogs mapped in this research (Figure 10), and as the foundations for individual turbines cover a circular area 90m in diameter (BOE, 2015), some of the smaller blanket bogs – such as Peña Ojastra – could be irreversibly damaged, or at worst, lost. As these edge-of-range examples of blanket bog contain a palaeoenvironmental archive for the region dating back more than 8500years (Ramil-Rego *et al.*, 2018), and the vegetation here may have distinctive genetic attributes, the loss of these landforms would be highly significant, not just for loss of long-term terrestrial carbon storage.

Despite the clear impact that windfarm installations can have on blanket bog, within a review of threats to habitats in the EU, windfarms are only considered to represent the ninth most important threat to these ecosystems, behind grazing, fire and afforestation (European Comission, 2012). However, and perhaps more significantly, none of the blanket bogs mapped in detail in this study, nor those mapped in Chico *et al.* (2019a), currently have protection through any form of conservation measure. Without any legislative protection there is a very real risk that these landforms will be lost. Urgent action is required from the regional governments of Cantabria and Castilla y León if these edge-of-range blanket bogs are to survive in the long term, while designation as part of the Natura 2000 network would enable the EU to provide financial support for the restoration and long-term conservation of these areas.

Conclusion

This study has provided a geo-hydromorphological assessment of 10 formerly unrecorded areas of blanket bog in the Cantabrian Mountains of north Spain. These blanket bogs currently represent the southernmost known limit of this habitat in Europe, and, combined with other recently identified blanket bog habitat in this area, may represent 10.5% of the blanket bogs currently recognized in Spain. These important landforms merit inclusion in the Spanish and European peatland inventories.

Despite the importance of these landforms for terrestrial carbon storage and associated palaeoenvironmental archive, high levels of anthropogenic pressures have had, and continue to have, substantial negative impacts on these newly identified areas. Windfarm installations have already significantly altered the functioning of some of these ecosystems, and without urgent protection some of the blanket bogs identified here may soon be lost. Action of a most urgent nature is needed from the governments of Cantabria and Castilla y León in order to retain what remains and restore these systems to important natural carbon sinks.

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Data Availability Statement

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

There is no conflict of interest in this paper.

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