Application of terrestrial laser scanning to quantify surface changes in restored and degraded blanket bogs

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SUMMARY

Many recognised areas of blanket bog are degraded, but the inventory and rate of loss of blanket bog globally is not fully known. Rapid identification of the rate and drivers of erosion and peat loss in blanket bogs more widely could inform localised approaches to protection and restoration of these important ecosystems. This study developed the application of Terrestrial Laser Scanning (TLS) to quantify the rate of surface change in restored and degraded blanket bogs by adopting a single scan strategy with fixed ground markers for repeat scanner location and fixed reference markers for scan alignment. Three recently mapped and remote areas of blanket bog in the Cantabrian Mountains (northern Spain) were scanned in May 2017 and July 2017 with a portable TLS (FARO X330) and 3D change in exposed peat surfaces was determined using a mesh to cloud (M2C) algorithm. The mean resolution of scan data across the sites was <3 mm, and where reference markers remained visible the maximum error of scan alignment was <1 mm, increasing to 6.5 mm where markers were obscured or lost. The rate of erosion determined over two months at Zalama (a protected blanket bog where reference markers were not disturbed) was -5.9 ± 4.6 mm (mean ± SD), but significantly higher ($p < 0.001$) rates of erosion and peat loss were determined for two unprotected blanket bogs under grazing regimes at Ilsos de Zalama (-22.9 ± 20.5 mm) and Collado de Hornaza (-35.7 ± 37 mm). This rate of change is already equal to the mean annual rate of erosion reported for bare peat in England and Wales (22.4–23.1 mm yr^{-1}) and for Scotland (36.3 mm yr^{-1}). This study demonstrates that portable TLS units can be used to make rapid assessment of surface change (erosion and peat loss) in blanket bog and indicates that trampling by cattle and horses is significantly increasing the rate of peat surface change in unprotected blanket bog in north Spain. This technique has direct application for peatlands under grazing regimes globally, and further installation of fences around blanket bog in northern Spain may be required imminently to reduce the loss of peat, the associated carbon store and priority habitat.

KEY WORDS: LiDAR, livestock trampling, northern Spain, peat erosion, peatland, peat loss

INTRODUCTION

Known peatlands cover less than 3 % of the global land surface (Matthews & Fung 1987, Moore 2002, Schumann & Joosten 2008), yet the peat accumulated in these ecosystems represents the largest store of terrestrial carbon (600 Pg (1 Pg = 10^{15} g); Yu *et al*. 2010). Around 75 % of peatlands (350 million ha) are found in the Northern Hemisphere across parts of Europe, North America, Canada and Russia (Gorham 1991). Although these accumulations are assumed to act as long-term carbon sinks, 65 million ha of peatland are reported as damaged or degraded, and in these states release 5–6 % of global greenhouse gases (Joosten 2009). Long-term increases in dissolved organic carbon (DOC) via fluvial pathways have also been noted from northern peat soils (e.g. Stoddard *et al.* 2003, Vourenmaa *et al.* 2006, Clutterbuck & Yallop 2010), and in eroding peatlands the major component of fluvial carbon loss is particulate organic carbon (POC; Evans *et al.* 2006). Quantification of peatland surface change, particularly erosion and peat loss, is therefore key to understanding the rate and drivers of peatland loss.

Rare peatland types, particularly raised and blanket bogs, are also internationally recognised for unique and endemic flora and fauna (Ratcliffe & Thompson 1988), so the rate of loss of peat from these areas may also serve as an indicator of the condition and rate of loss of globally important habitats. Blanket bogs are predominantly found in areas with an oceanic climate between latitudes 45° and 60° including the east coast of Canada, the North American Pacific coast, Tierra del Fuego (South America), north-east Asia, New Zealand, the Southern Ocean Islands and the west coast of Europe (Lindsay *et al.* 1988). European blanket bogs are mainly found in Norway, Ireland and Great Britain (Lindsay 1995), with some occurrence in Sweden, France and Spain (Joosten *et al.* 2017). The majority

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of areas of blanket bog currently mapped in Spain are located in the north-west in Galicia (Joosten *et al.* 2017), although a number of areas have recently been identified between Cantabria and Bizkaia in the eastern area of Cantabrian Mountains (Heras 2002, Chico *et al*. 2019).

Most northern peatlands formed over the last 10,000–15,000 years with peat accumulations ranging up to 6–7 m in depth (Charman 2002). In Spain, the rate of peat accumulation in blanket bogs during the Holocene has been estimated at 0.4–0.5 mm yr^{-1} and in Galicia continues at a rate of 0.45 to 0.47 mm yr^{-1} (Castillo *et al.* 2001). Although higher rates of accumulation (0.75 mm yr^{-1}) have been reported in Nordic countries (Aaby 1986), the current rate of peat accumulation in Spain is comparable to lower rates of accumulation in the UK (0.5–1 mm yr^{-1}; Lindsay 2010). In the Cantabrian Mountains (north Spain), blanket bogs are mainly located on peaks with N–NW orientations where fog and high humidity is common (200 days/year; Onaindía & Navarro 1985). However, topography (specifically high slopes >25°) has limited blanket bog development (Heras & Infante 2008) and peat accumulations here are typically found up to 3 m deep (Castillo *et al.* 2001, Heras & Infante 2003, Chico *et al*. 2019).

Erosion and peat loss from blanket peat has been studied extensively in the UK (Evans & Warburton 2007), and highlighted, but not always quantified, in countries including Ireland (McGreal & Larmour 1979), Canada and Sweden (Foster *et al.* 1988), and Spain (Castillo *et al.* 2001, Heras & Infante 2003, Heras & Infante 2018). The rate of erosion is affected by natural processes, while peat loss can arise from a combination of natural and anthropogenic influences, though aeolian, fluvial and freeze-thaw processes are identified as key drivers of surface change (Bower 1961, Labadz 1988, Campbell *et al*. 2002). Anthropogenic activities including drainage (Holden *et al*. 2006, Luscombe *et al.* 2016), peat extraction (Price *et al.* 2003, Lindsay 2010), overgrazing (Castillo *et al.* 2001, Ward *et al.* 2007), prescribed burning (Yallop *et al.* 2006, Yallop & Clutterbuck 2009) and wildfire (Yeloff *et al.* 2006, Heras & Infante 2018) have also been highlighted as influencing peat degradation. Bog-bursts may be initiated by wind farms and associated infrastructure (Lindsay & Bragg 2005), and the installation of wind turbines on blanket bog is a contentious issue (Wawrzyczek *et al.* 2018), particularly in north Spain (Castillo *et al.* 2001, Heras & Infante 2008, Chico *et al*. 2019), where a number of areas of peat, including blanket bog, are currently not mapped and therefore not protected.

The mean rate of erosion for bare peat surfaces across the UK is estimated at 2.3 cm yr^{-1}, although in some places rates of change are less than 1 cm yr^{-1} (Evans & Warburton 2007). Such fine-scale erosion in peatlands has traditionally been determined using erosion pins (e.g. Labadz *et al.* 1991, Evans *et al.* 2006) and sediment traps (Evans & Warburton 2007), although the spatial extent of assessment using these approaches is significantly limited (Boardman & Favis-Mortlock 2016). In addition, erosion pins can be moved and their presence influences erosion (Couper *et al*. 2002). Assessments of erosion features over larger areas of peatland have employed remote sensing techniques such as conventional aerial photography (Bower 1961, Tallis 1973, Natural England 2012) and airborne LiDAR (Walsh *et al*. 1998, Evans & Lindsay 2010), but the spatial resolution of both these technologies (typically 25 cm at best for commercial off-the-shelf (COTS) products covering areas of peatlands) constrains the scale of erosion detectable (Clutterbuck *et al.* 2018). While higher resolution data can be obtained from bespoke, commissioned surveys, these technologies are still suited to longer-term assessment of change in peatlands owing to the accuracy (5–10 cm horizontal; 5–15 cm vertical; e.g. Bluesky International 2019).

The development of Structure-from-Motion (SfM) photogrammetry marked a major enhancement in geoscience (Westoby *et al.* 2012), and SfM approaches using Unmanned Aerial Vehicles (UAVs) and ground-based cameras are seeing wide application in peatland environments (Kalacksa *et al.* 2013, Knoth *et al.* 2013, Lehmann *et al.* 2016, Glendell *et al.* 2017, Lovitt *et al.* 2017, Smith & Warburton 2018). Ultra-high resolution imagery achievable with these techniques (<1 cm) are beginning to see direct application for quantifying rates of peat erosion (Glendell *et al.* 2017). Terrestrial laser scanning (TLS) using ground-based LiDAR is commonly used as a benchmark to assess the accuracy of SfM techniques (Castillo *et al.* 2012, Eltner *et al*. 2013, Gómez-Gutiérrez *et al.* 2014, Ouédraogo *et al.* 2014, Smith & Vericat 2015, Neugirg *et al.* 2016), and indicates that for peatland erosion, SfM vertical errors range from 3–35 cm (Glendell *et al.* 2017).

Terrestrial laser scanning (TLS) has advanced rapidly in the last decade, with TLS units now more portable and capable of recording 1 million points (pts) s^{-1} providing ultra-high-resolution 3D data (< 2 mm point spacing) with accuracies of 1 mm at 10–15 m from the scanner (Idrees & Pradhan 2016). The area captured using TLS is significantly less than areas covered in airborne surveys, but point cloud data derived from TLS retain the complex

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morphology of surfaces such as overhanging topography and allow 3D comparison of change (Lague *et al*. 2013, Ordóñez *et al*. 2018). TLS technology is seeing wide application for assessing change in a range of environments including alpine (Schürch *et al*. 2011) and proglacial river channels (Milan *et al*. 2007), meandering gravel beds (O'Neal & Pizzuto 2011), bedrock rivers (Lague *et al*. 2013), rill (Lu *et al*. 2017) and bluff erosion (Day *et al*. 2013), badland landforms (Neugirg *et al*. 2016), and sub-tropical vertosol gullies (Goodwin *et al*. 2016). To date, however, TLS has seen limited application for assessing erosion in peatlands (Grayson *et al*. 2012, Glendell *et al*. 2017). Several challenges have been noted in peatland environments (Grayson *et al*. 2012), as dense vegetation may inhibit assessment of the surface, and morphological change arising from 'mire breathing', where the peat surface can change vertically and horizontally in response to gaseous exchange (typically CH_4) or water content in the peat body (Schlotzhauer & Price 1999, Glaser *et al*. 2004), could be greater than the scale of erosion occurring.

Although erosion has been highlighted as a significant issue for peatlands in north Spain (Heras & Infante 2003, Chico *et al*. 2019), there are currently no published data on erosion or peat loss. Therefore, this study 1) evaluates the application of portable TLS in peatland environments to make rapid assessment of rates of surface change for blanket bogs and 2) assesses differences in the rate of surface change between designated blanket bog undergoing restoration (erosion rates) and otherwise comparable unprotected blanket bog in the Cantabrian Mountains (peat loss and erosion).

METHODS

Study sites

This study focuses on three areas of blanket bog (Zalama, Ilsos de Zalama and Collado de Hornaza; Figure 1) located on the regional mountain borders of Cantabria, País Vasco (Basque Country) and Castilla y León in northern Spain. The mountain ranges are composed of sandstone and shale from the Cretaceous Period (GeoEuskadi 2017, Mapas Cantabria 2017) and are covered by acidic, nutrient poor soils (Heras 2002). The oceanic climate provides 200 rain days (>1,600 mm per year) and an annual mean temperature of 7.5 °C (Heras & Infante 2003). During the research reported here (May–July 2017), climatic conditions across all study sites were comparable with mean air temperature ranging from 13.1 °C to 13.8 °C, mean wind speed between 11.6–12.5 km/h, humidity from 79.5 %–80.4 % and rainfall from 124.6 mm to 135.1 mm (meteoblue 2017). There is no arid season as in summer months occult precipitation continues from cloud that encompasses the mountain tops. In combination with the low permeability of the geology, these conditions have

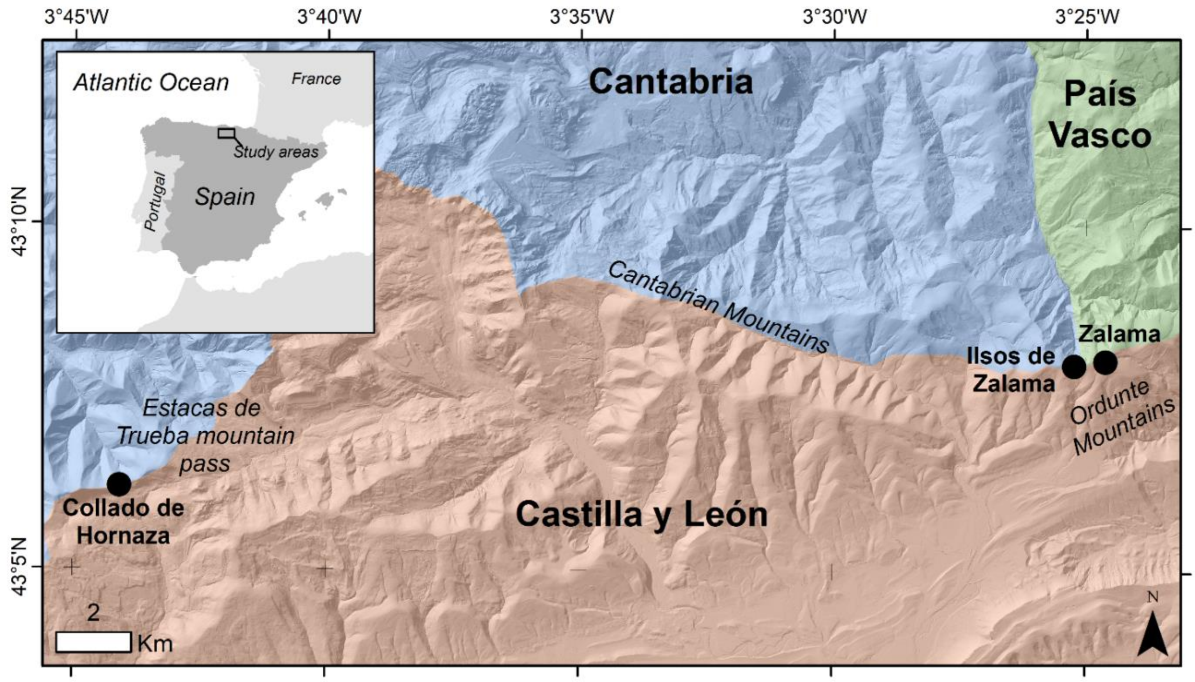

Figure 1. Locations of the three study sites, namely Zalama blanket bog, Ilsos de Zalama blanket bog and Collado de Hornaza blanket bog.

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allowed peatlands to form on many areas along the Cantabrian Mountains (Heras & Infante 2003).

Vegetation across these areas is characterised by a cover of ericaceous shrub (*Calluna vulgaris*, *Erica* spp. and *Vaccinium myrtillus*), Cyperaceae (*Eriophorum* spp.) and Juncaceae (*Juncus* spp.). In wetter areas *Sphagnum* spp. are common (Heras 1990), but rarer plants such as Droseraceae (*Drosera* spp.) are less abundant; for example, *Drosera rotundifolia* has only recently been recorded at Zalama (Chico & Clutterbuck 2018).

Zalama

Zalama (43° 8′ 3.62″ N, 3° 24′ 38.72″ W) is a blanket bog (Heras 2002, Chico *et al.* 2019) located in the Ordunte Mountains (Basque Country/Castilla y León) at an altitude of 1330 m above sea level (m a.s.l). Peat covers an area of approximately 6.3 ha ranging up to 2.82 m deep (Chico *et al.* 2019) and basal layers have been dated at 8,000 years old (Souto *et al.* 2014). Zalama is currently the only site in this study that has blanket bog designation in Natura 2000 and, although degraded, has undergone several approaches to protect and restore the bog. In 2008, a fence was installed around the perimeter of the main peat body covering 3.4 ha to exclude large grazing livestock (specifically cattle and horses) and additional fencing was installed in 2018 to protect a further 2.6 ha of the bog margin. Subsequently, areas of exposed peat ranging from horizontal to slopes of up to 30° have been covered with geotextile (coconut fibre sheets) held in place using square wooden frames (Figure 2A) and planted with *Eriophorum vaginatum* under LIFE+ Ordunte Sostenible funded by the European Union and Bizkaia Provincial Council. A number of vertical, concave peat faces are however still exposed (Figure 2A).

Ilsos de Zalama

Ilsos de Zalama (43° 7′ 58.33″ N, 3° 25′ 16.63″ W) is located approximately 500 m to the west of Zalama at an altitude of 1270 m a.s.l. Peat covers an area of approximately 3.1 ha ranging up to 2.16 m deep (Chico *et al*. 2019). The peatland is characteristic of saddle mire with a central raised portion indicating ombrotrophic status (Chico *et al.* 2019). The blanket bog is degraded with several near horizontal areas of exposed peat (Figure 2B) and a raised ‘tongue’ of intact peat with vertical, concave exposed peat faces on all sides. In contrast to Zalama blanket bog, there are no structures to protect the exposed peat and livestock graze the area between April and October.

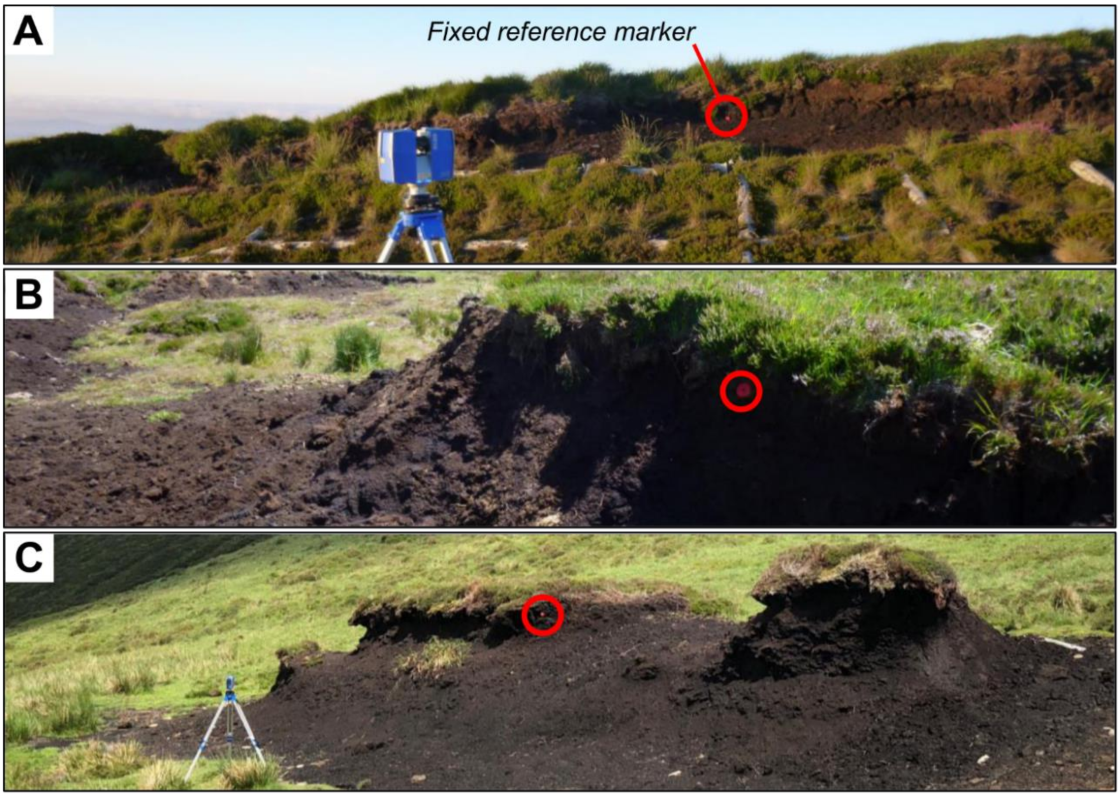

Figure 2. Study areas. A) Zalama blanket bog with example of restoration geotextile material, B) Ilsos de Zalama blanket bog, C) Collado de Hornaza blanket bog. Photographs taken by Guaduneth Chico in May 2017.

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Collado de Hornaza

Collado de Hornaza (43° 6′ 12.37″ N, 3° 44′ 1.57″ W) is located approximately 3 km south-west of the mountain pass Estacas de Trueba between Cantabria and Castilla y León administrative regions (Figure 1). The site is approximately 25 km west of Zalama at an altitude of 1280 m a.s.l. Peat accumulation at Collado de Hornaza extends northwards creating a sloping blanket bog and covers an area of approximately 3 ha ranging up to 2.75 m deep (Chico *et al.* 2019). Exposed peat at Collado consists primarily of two 'islands' with vertical, concave exposed peat faces on all sides (Figure 2C). Similar to Ilsos de Zalama there is no protection of the peat from livestock, and in addition to grazing, burning of vegetation to improve browse is undertaken locally from November to April.

Terrestrial laser scanning

Each site was scanned on one day between 22nd and 23rd May 2017 and again between 16th and 18th July 2017 using a FARO Focus3D X330 terrestrial laser scanner. The X330 is suited to remote surveys owing to the relatively small size and low weight (5.2 kg), and the unit has a maximum range of 330 m with a ranging error of ±2 mm. The scanner is phase based, measuring phase shift in pulses sent at a wavelength of 1550 nm, and was set to operate at maximum resolution (sending up to 976,000 pts s^{-1}). The step size at this resolution is 0.009°, which is reported to achieve a point spacing of 1.5 mm at a distance of 10 m from the scanner. Scanner 'quality' settings relate to the confidence in a distance measurement determined by the number of repeat measurements used to derive an average distance for each individual 'point'. This has advantages for objects that might move during scan collection such as vegetation, but since the feature of interest was exposed peat, the second highest setting of quality was selected which reduced the time of individual scans from 2 h to 31 min.

To exclude potential error introduced by registering/aligning multiple contemporaneous point clouds (Smith 2015), the approach for this study adopted a single scan on each date. A fixed ground reference marker was installed in the bedrock on the first scan to allow precise positioning of the tripod and scanner in repeat surveys (Figure 3). On each survey date, scans were repeated from the same location to allow assessment of scanner error. All survey areas were within 16 m of the scanner and 60 % of the areas were within 10 m.

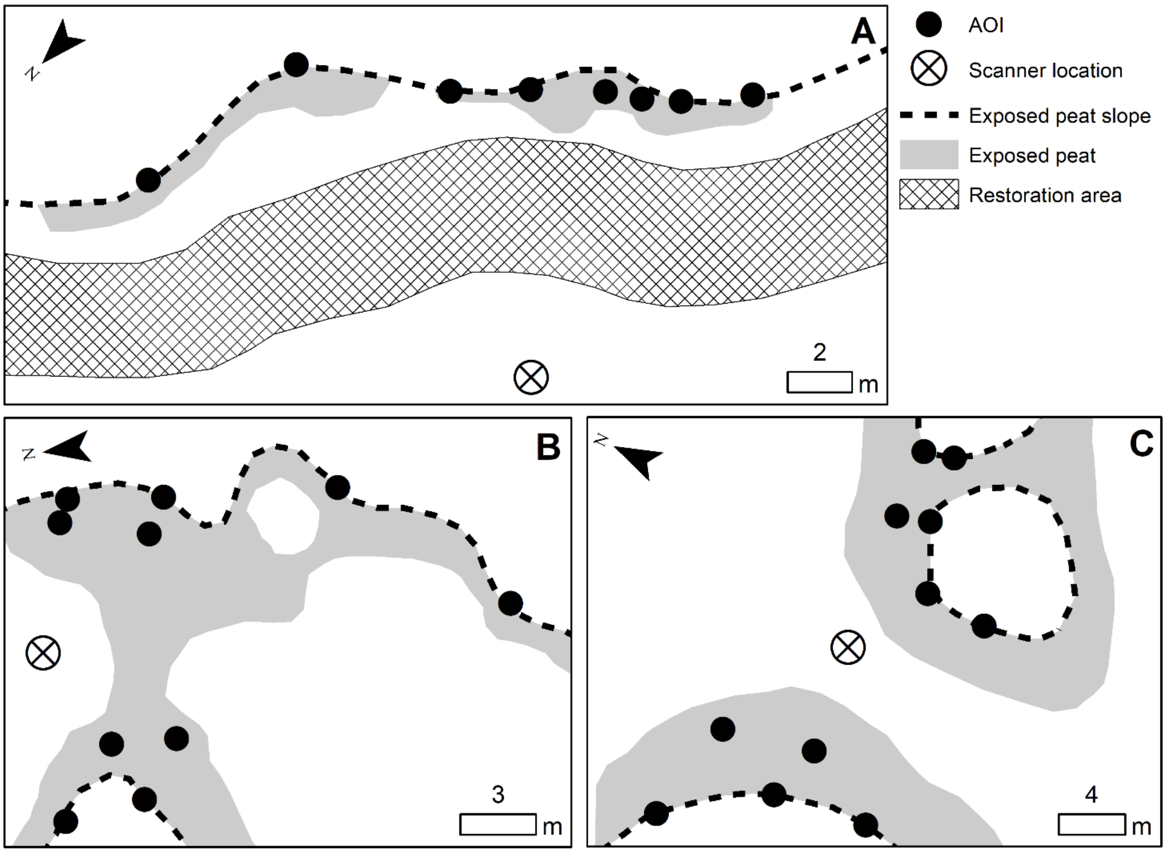

Figure 3. Schematic of study areas and survey strategy. A) Zalama, B) Ilsos de Zalama, C) Collado de Hornaza. Black circles indicate the centre of the selected AOI.

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Survey area selection and fixed reference markers

To mitigate damage to the sensitive vegetation and exposed peat across the areas, a single scanning location for the largest area of exposed peat present at each site, oriented approximately N–NW, was selected. At Zalama the survey area comprises a near vertical peat face with low-angle sloping surfaces extending out from the base, while for Ilsos de Zalama and Collado de Hornaza, it was possible to capture several near vertical peat faces and low-angle sloping surfaces.

Four fixed reference markers were inserted into the peat faces at each site to improve the accuracy of multi-temporal scan data alignment. Markers were 60 cm in length with a red circular end 5 cm in diameter that contrasts against the colour of exposed peat surfaces (e.g. Figure 2).

Scan data processing and registration

Data from the scanner were imported and processed initially using FARO Scene Version 6. Point clouds were colorized using the photographs captured by the scanner to improve identification of fixed reference markers. The data were filtered in FARO Scene using a stray point algorithm provided in the software to remove erroneous data points resulting from dust particles or water vapour in the air, and subsequently using an edge artefact filter to remove noise around edges of features such as slumped blocks of peat.

Scan point clouds were registered using the fixed reference markers as reference points and were left in a local coordinate system with the scanner location as the origin. To align scan point clouds, the x, y, and z local coordinate for each fixed reference marker from the first scan was applied to the same markers in subsequent scans and registered. The point cloud for each scan was exported separately for comparison and clipped to the area of exposed peat to remove returns from objects outside the area of interest. It was apparent in the July survey that at Ilsos de Zalama two fixed reference markers had been covered by slumping peat and at Collado de Hornaza two fixed reference markers had been physically removed by an unknown person or animal. For registration of these scan data, two areas of bedrock were used as extra reference points in addition to the two remaining fixed markers.

Area of interest selection

Between May and July changes in vegetation obscured parts of each study site that were surveyed in May. Therefore, the total point cloud for each site was reduced to comprise multiple individual areas of interest (AOI, Figure 3) that were visible in both datasets and can be used for future comparison. In addition to vegetation, areas with obstructions such as rocks or geotextiles (in Zalama) were also excluded as change in their morphology was not of interest. The number of AOIs identified ranged from 8 AOI at Zalama covering the area of exposed peat above the restored area (Figure 3A), 10 AOI at Ilsos de Zalama (Figure 3B) and 12 AOI in Collado de Hornaza (Figure 3C). For all sites these AOI cover a range of near vertical peat faces and low-angle sloping areas.

Error assessment

To assess scanner error, the point cloud for the repeat scan at each AOI was compared with the first scan using the point to point comparison tool (C2C) in CloudCompare software. This tool measures distances between two clouds using the Hausdorff distance (Girardeau-Montaut *et al.* 2005) and any difference determined in point location here quantifies variation in scan geometry. Potential increase in error with distance from scanner in the point clouds was tested using Pearson's correlation. Registration error for the alignment of the scans taken in May and July 2017 at each site were reported in FARO Scene and extracted for each study area.

Determining surface difference and volume change

To quantify change between May and July 2017, the point cloud for the scan taken in May at each survey site was converted to a 3D mesh using FARO Scene and output at maximum data resolution (Table 1). The mesh was exported and compared with the point cloud from July data for each AOI using the Mesh to Cloud (M2C) algorithm in CloudCompare. This method determines the signed distance between each point in July and the mesh data from May, and creates a new point cloud where each point has the signed distance assigned (Monserrat & Crosetto 2008).

To compare overall change between sites, points from all AOI at each site were combined and the mean (overall) surface difference between May and July calculated for all sites. As the mean difference in each site will obscure the magnitude of both positive and negative change, the data were split by signed values and the mean negative and mean positive surface changes determined separately for each site. Subsequently, the mean difference between May and July surfaces was calculated for individual AOI in all sites. Mean negative and mean positive surface change for each AOI were determined separately and volume change by unit area determined for each AOI.

As the data for all sites were not normally distributed, the values of difference (change) determined for each site were compared to the values of difference for the other two sites using the Mann-Whitney test (Mann & Whitney 1947). This was

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undertaken first using all difference values and then on all negative and all positive difference values separately. All analyses were undertaken using RStudio version 1.1.456.

RESULTS

Survey areas, point cloud density and mesh resolution

The total surface area of combined AOI varied between sites, with the smallest area assessed in Zalama (11.7 m^2; Table 1). This difference largely arises from the nature of the sites and exposed peat surface available for survey, particularly the reduction in exposed peat at Zalama following restoration activities (Figure 2A). Mean point cloud densities across the sites ranged from 163,698 to 555,260 pts m^{-2} (Table 1), and relate to distance from the scanner (Table 2). If the points were evenly distributed in the data this would equate to a mean point spacing of 1.3–2.3 mm. Of particular note is that for each site the mean point density between surveys varied by <0.1 % (Table 1), indicating a consistent survey strategy.

Error assessment

Scanner error

Analysis of repeat scans showed that with the exception of two AOI in Ilsos de Zalama in May and two AOI in Collado de Hornaza in July (Table 2), the mean distance difference was <2 mm and falls within the reported ranging error of the scanner (±2 mm). The four instances of higher mean error were less than 4 mm indicating that at the distance surveyed here, error introduced by variations in scan geometry appears minimal. Error of scan geometry did not correlate with distance from scanner ($r = 0.22$, $p > 0.05$).

Registration error

For Zalama, where all four fixed reference markers were present in both surveys, the error of registration of May and July 2017 point clouds ranged from 0.6–0.8 mm (Table 3). Despite the loss of two fixed reference markers at both Collado de Hornaza and Ilsos de Zalama noted in July, scan registration error was still < 4 mm for Collado de Hornaza (0.7–3.7 mm) and < 7 mm for Ilsos de Zalama (4.8–6.5 mm).

Table 1. Survey area, point density and mesh resolution.

Site		Zalama	Ilsos de Zalama	Collado de Hornaza
Total survey surface area (m^2)		11.7	26.88	91.37
No. of points covering survey area				
	May	1,915,269	14,925,396	25,710,537
	July	1,903,390	14,962,164	24,556,916
Mesh resolution (no. of faces; May)		5,501,743	9,320,604	14,231,857
Variation in point density (May; pts m^{-2})				
	Mean	163,698	555,260	281,389
	Maximum	209,494	1,167,405	556,348
	Minimum	95,430	59,020	54,807
Variation in point density (July; pts m^{-2})				
	Mean	162,683	556,628	268,763
	Maximum	212,698	1,165,508	534,173
	Minimum	86,770	57,485	53,389

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Table 2. Surface area and scanner error for AOIs in each study site for May and July 2017.

AOI	Surface area (m^2)	Distance from scanner (m)	May		July	
			Mean error (mm)	SD (mm)	Mean error (mm)	SD (mm)
Zalama						
1	1.51	11.2	0.40	1.3	0.50	2.1
2	1.26	9.8	0.01	2.1	0.20	2.0
3	1.38	9.3	0.30	0.9	0.20	0.9
4	1.00	9.2	0.60	0.7	0.60	0.7
5	4.10	8.9	0.60	1.8	0.40	2.3
6	0.81	9.2	0.70	1.9	0.20	6.0
7	0.32	12.1	1.40	1.6	0.50	2.9
8	1.32	13.4	1.40	3.4	0.05	13.5
Mean		**10.4**	**0.70**	**0.5**	**0.30**	**0.2**
Ilsos de Zalama						
1	3.00	6.8	1.70	2.6	1.20	1.9
2	6.33	4.6	0.40	2.0	1.40	2.4
3	0.55	7.1	2.70	2.6	0.30	1.6
4	3.18	6.3	1.10	2.1	0.40	3.2
5	1.57	15.9	0.70	3.3	1.20	3.5
6	0.66	13.5	3.90	3.6	0.10	2.6
7	2.41	7.8	1.20	2.2	0.30	2.1
8	6.63	6.3	0.70	2.0	0.10	2.5
9	1.41	6.2	0.10	2.1	0.50	1.7
10	1.14	5.2	0.01	1.8	0.70	1.2
Mean		**8**	**1.60**	**1.2**	**0.60**	**0.5**
Collado de Hornaza						
1	5.63	15.9	1.50	1.3	2.70	3.3
2	1.93	12.6	0.90	1.4	1.30	3.0
3	6.44	8.4	0.80	1.3	1.70	2.4
4	4.71	13	0.40	1.0	0.80	2.2
5	4.40	9	0.90	1.1	1.20	3.9
6	19.86	5.8	0.04	1.5	3.20	3.7
7	3.14	8.3	0.30	1.2	0.70	4.7
8	11.66	10.8	1.40	1.8	0.50	3.7
9	11.35	10	0.40	2.3	0.70	3.6
10	14.31	6.7	0.90	1.5	0.20	2.7
11	1.97	9.1	0.30	0.8	0.30	2.6
12	5.97	15.4	0.10	1.7	0.80	3.6
Mean		**10.4**	**0.70**	**0.5**	**1.50**	**1**

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Table 3. Accuracy of point cloud registration.

Site	Mean (mm)	SD (mm)	Min (mm)	Max (mm)
Zalama	0.7	0.1	0.6	0.8
Ilsos de Zalama	5.4	0.8	4.8	6.5
Collado de Hornaza	2.7	1.4	0.7	3.7

Table 4. Mean surface difference for all study sites.

	Mean surface difference (mm)	SD	Proportion of point data (%)
Zalama			
Overall	-2.8	6.9	100
Negative (erosion)	-5.9	4.6	72
Positive (deposition)	4.9	5.5	28
Ilsos de Zalama			
Overall	-6.8	28.7	100
Erosion	-22.9	20.5	63
Deposition	20.9	17.4	37
Collado de Hornaza			
Overall	-19.9	40.7	100
Erosion	-35.8	37.0	70
Deposition	17.3	18.8	30

Determining surface difference and morphological change

Peatland surface change by study sites

A negative surface difference was identified for the majority of points at each site between May and July 2017 (63–72 %; Table 4), indicating that erosion in Zalama and peat loss in Collado de Hornaza and Ilsos de Zalama are dominant surface processes occurring in the areas assessed. The overall mean surface difference for each site ranged from -2.8 ± 6.9 mm (mean ± SD) for Zalama, to -6.8 ± 28.7 mm at Ilsos de Zalama and -19.9 ± 40.7 mm at Collado de Hornaza (Table 4; Figure 4). The range of difference from the 1 % to 99 % percentiles determined at Zalama (36 mm) was four times lower than the range of values determined at Ilsos de Zalama (149 mm) and six times lower than the range of values determined at Collado de Hornaza (215 mm; Figure 4). A Mann-Whitney test identified that overall change at Zalama was significantly different to the change at both Ilsos de Zalama (W = 1.64e+13; $p < 0.001$) and Collado de Hornaza (W = 3.01e+13, $p < 0.001$), and that overall change was also significantly different between Ilsos de Zalama and Collado de Hornaza (W = 2.13e+14, $p < 0.001$).

Treating positively and negatively signed difference data separately highlights a greater magnitude of change at each site. The mean surface difference determined from negative values at Zalama indicated larger change compared to the overall mean difference (-5.9 ± 4.6 mm), but difference values of up to -22.9 ± 20.5 mm and -35.8 ± 37 mm were identified at Ilsos de Zalama and Collado de Hornaza respectively (Table 4). In addition, the mean surface difference determined from positive values (28–37 % of points) identified deposition ranging from 4.9 ± 5.5 mm at Zalama to 17.3 ± 18.8 mm and 20.9 ± 17.4 mm at Collado de Hornaza and Ilsos de Zalama, respectively (Table 4; Figure 4). While the maximum scan registration error for Ilsos de Zalama (6.5 mm) is of the same magnitude as mean overall change detected at this site (6.8 mm), the registration error is 3–4 times lower than the mean negative and mean positive change determined. A Mann-Whitney test identified that negative change at Zalama was significantly different to the change at Ilsos de Zalama (W = 1.07e+13, $p < 0.001$) and Collado de Hornaza (W = 1.97e+13, $p < 0.001$) and that the negative change was also significantly different between Ilsos de Zalama and Collado de Hornaza (W = 9.42e+13, $p < 0.001$). For positive values, a Mann-Whitney test identified a significant difference between positive change at Zalama and both Ilsos de Zalama (W = 4.94e+11, $p < 0.001$) and Collado de Hornaza (W = 9.65e+11, $p < 0.001$). Positive change was also significantly different between Ilsos de Zalama and Collado de Hornaza (W = 2.37e+13, $p < 0.001$).

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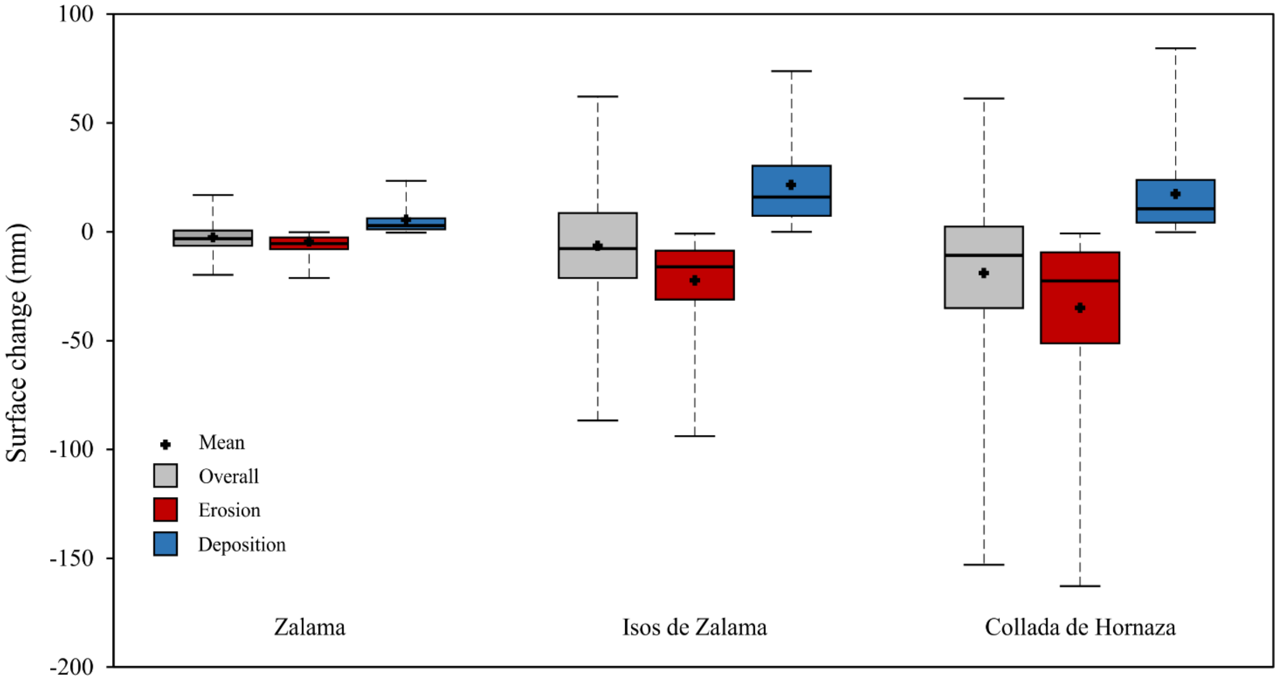

Figure 4. Distribution of surface change values for Zalama, Ilsos de Zalama and Collado de Hornaza showing 1 %, 25 %, 50 %, 75 % and 99 % percentiles.

Peatland surface change by AOI

At Zalama, the mean overall surface change measured for all AOI between May and July 2017 was negative (Figure 5). Mean overall surface change measured in AOI at Collado de Hornaza and Ilsos de Zalama was also predominantly negative, except for two AOI at Collado de Hornaza and three AOI at Ilsos de Zalama that produced a positive overall mean change, indicating that deposition may be a dominant surface process in some AOI (Figure 5).

There is a clear difference in the variability and magnitude of overall change between the sites assessed, as for Zalama mean overall change for all AOI ranged from -8 mm to -1 mm while at Ilsos de Zalama and Collado de Hornaza mean AOI change figures of -40 mm to +6 mm and -67 mm to +9 mm respectively were noted (Figure 5). This contrast between sites is even greater when positively and negatively signed points were analysed separately; for Zalama the range of mean AOI erosion compared to overall change increases by 1.4 mm to -9.4 mm, whereas for Ilsos de Zalama and Collado de Hornaza particularly, mean AOI erosion plus peat loss of up to -42.6 mm and -82.1 mm were noted (Figure 6). Interestingly the proportion of points contributing negative values for the larger estimates in these two AOI was 95 % at Ilsos de Zalama and 87 % at Collado de Hornaza (Table 5).

It is also interesting to note that when analysing positively signed points separately all AOI indicate some level of deposition occurring (Figure 6). At Zalama all estimates of deposition are lower than 7 mm, but at Ilsos de Zalama 10 of the 11 AOI indicate rates of deposition over 10 mm with two AOI indicating up to 28 mm and at Collado de Hornaza 11 of the 12 AOI indicate rates of deposition over 10 mm and the AOI where -82 mm of erosion/peat loss was recorded indicated that up to 34 mm of deposition had occurred. It should be noted that the large deposition identified at this AOI in Collado de Hornaza was derived from only 13 % of the points recorded; at Ilsos de Zalama both larger estimates of deposition were derived from 22–59 % of the points for the AOI (Table 5).

At least two of the AOI assessed at each site solely comprised sections of near vertical peat and it is clear that the two highest measurements of erosion in AOI at Ilsos de Zalama (-40.9 to -42.7 mm) and three highest measurements of erosion in AOI at Collado de Hornaza (-39.2, -42.3 and -82.1 mm) were identified for near vertical sections of exposed peat (ILZ5 & ILZ7; CH8, CH9 & CH12; see the additional information provided in the Appendix). For the AOI with the highest erosion measured at -82.1 mm (CH9), the overall volume change is -0.068 $m^3 m^{-2}$ (Figure 5).

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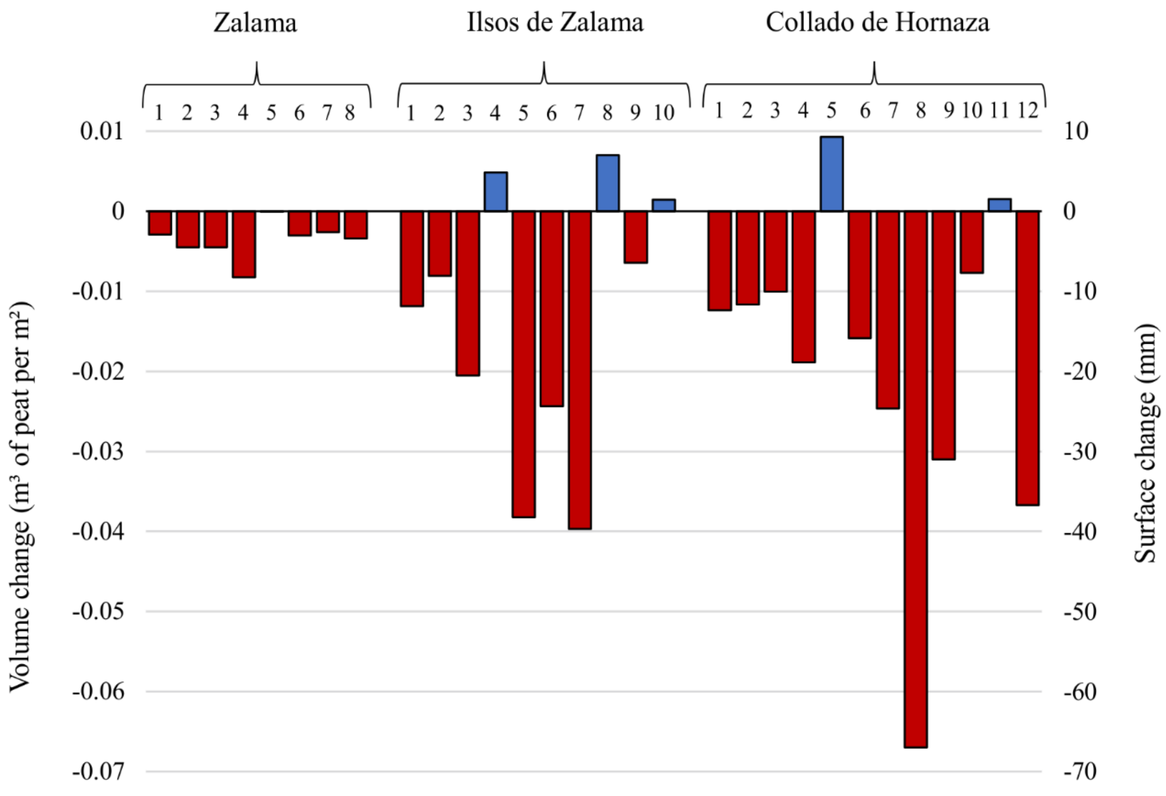

Figure 5. Mean peat volume change and mean surface change in each AOI.

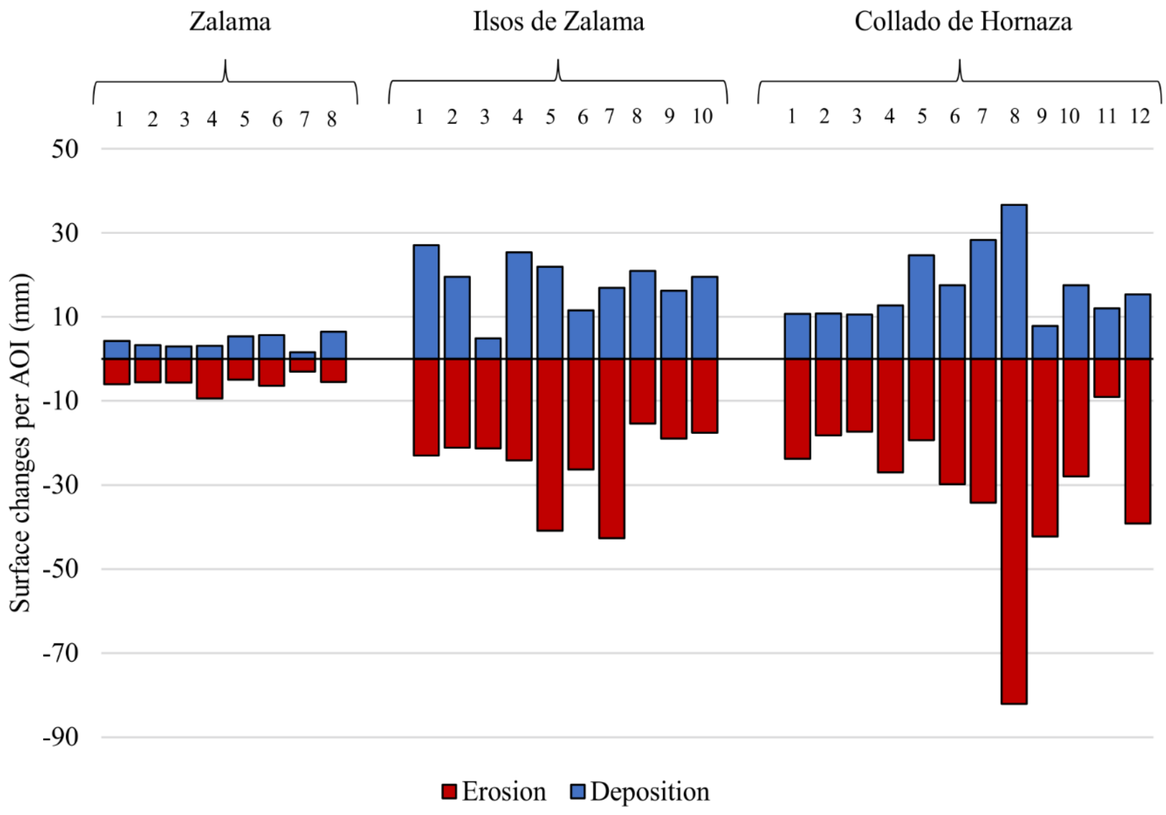

Figure 6. Mean positive (deposition) and mean negative (erosion) surface change measured by AOI.

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Table 5. Proportion of points in surface differences for each AOI.

Site	AOI	% Accumu-lation	% Erosion/ Peat loss
Zalama	*LZ1*	30.3	69.7
	LZ2	99.3	0.7
	LZ3	13.0	87.0
	LZ4	9.3	90.7
	LZ5	47.8	52.2
	LZ6	27.7	72.3
	LZ7	8.3	91.7
	LZ8	17.5	82.5
Ilsos de Zalama	*ILZ1*	22.3	77.7
	ILZ2	32.1	67.9
	ILZ3	2.8	97.2
	ILZ4	58.6	41.4
	ILZ5	4.3	95.7
	ILZ6	5.2	94.8
	ILZ7	5.0	95.0
	ILZ8	61.7	38.3
	ILZ9	35.6	64.4
	ILZ10	51.2	48.8
Collado de Hornaza	*CH1*	33.1	66.9
	CH2	22.7	77.3
	CH3	26.2	73.8
	CH4	20.4	79.6
	CH5	65.1	34.9
	CH6	29.5	70.5
	CH7	15.3	84.7
	CH8	12.7	87.3
	CH9	22.6	77.4
	CH10	44.6	55.4
	CH11	50.2	49.8
	CH12	4.1	95.9

DISSCUSION

Applicability of TLS for assessing peatland erosion and peat loss

Rates of erosion and peat loss in peatlands vary spatially and temporally. Recent advances in the spatial resolution of data derived from geospatial technologies have allowed increased application of remotely sensed data for monitoring peatlands (Clutterbuck *et al.* 2018), and data from both UAV-mounted and ground-based cameras (Glendell *et al.* 2017), and TLS (Grayson *et al.* 2012, Glendell *et al.* 2017) are seeing direct application for quantifying rates of erosion in peatlands with mm resolution.

Estimation of change using any remote sensing approach requires comparable resolution of repeat survey data and quantification of errors associated with the technique. Terrestrial laser scanning is used widely in erosion studies (e.g. Milan *et al.* 2007, O'Neal & Pizzuto 2011, Schürch *et al.* 2011, Goodwin *et al.* 2016, Dąbek *et al.* 2018) capturing ultra-high resolution data comprising over 80,000 pts m^{-2}. Where multiple scans overlap, resolutions of over 390,000 pts m^{-2} have been reported close to the scanner (Brasington *et al.* 2012), yet in studies assessing peatlands, resolutions of TLS data range from 24 pts m^{-2} (Höfle *et al.* 2013) to 4,800 pts m^{-2} (Glendell *et al.* 2017). TLS was adopted in this study to quantify the rate of surface change in three blanket bogs in northern Spain and mean resolution of data obtained across the sites ranged from 163,698–555,260 pts m^{-2} (Table 1). If the points were evenly distributed across the surface this would equate to a mean point spacing of 1.3–2.3 mm, and highlights the need for extremely high levels of accuracy to enable comparison of survey data.

Errors in TLS data arise from a number of sources including the scanner specification and operational settings (ranging error, beam divergence and data 'quality'), environmental factors (presence of vegetation, dust particles and water vapour) and point cloud registration/alignment, specifically relating to registration target type, number, distribution and position (often recorded using differential GNSS; Hall 2016, Grayson *et al.* 2012, Smith 2015).

For all three sites assessed, the scanner was located within 15.9 m of the survey areas and this may explain the far higher resolution of data obtained compared with other studies assessing peatland surface change (Grayson *et al.* 2012, Höfle *et al.* 2013, Glendell *et al.* 2017). Of particular note however is that the resolution of scan data in this study varied by <0.1 % between surveys. Smith (2015) highlights the impact of using different scanner resolution and also of data quality settings on

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point cloud error and this was mitigated by adopting the same scanner settings in each scanning campaign. Variation of scan geometry could impact upon the accuracy of the data, although comparison of repeat scan data indicates that the mean error of point location between scans was < 2 mm for 26 of the 30 AOI assessed. Larger error recorded for four of the AOI was still < 4 mm (2.7–3.9 mm) and did not increase with distance from scanner. These observations indicate that at the range employed here, the impact of variation in scan geometry and beam divergence on data collected using the FARO X330 appears minimal.

All scans were undertaken when conditions were clear (i.e. no visible water vapour in the air), although stray point filtering was used to remove erroneous data points that may have included water vapour or dust particles. The impact of vegetation obstructing survey areas is commonly noted (e.g. Grayson *et al.* 2012, Hall 2016, Dąbek *et al.* 2018), and changes in vegetation between surveys in this study did present a problem by obscuring sections of the survey area. Filters could be used to remove the vegetation (Dąbek *et al.* 2018, Ordóñez *et al.* 2018) but to prevent false identification of change, only those areas where exposed peat was openly visible were selected by excluding areas of vegetation, rocks and geotextile.

The largest source of error in TLS data occurs in the registration of multiple scan point clouds (either contemporaneous or multi-temporal; Smith 2015). To assess change in areas larger than that assessed here, multiple contemporaneous TLS scan data are frequently combined (Milan *et al.* 2007, Schürch *et al.* 2011, Grayson *et al.* 2012, Höfle *et al.* 2013, Hall 2016, Glendell *et al.* 2017); however, in this study, single scans were used for each temporal survey to remove any potential error associated with this process. Therefore, registration error was limited to the alignment of individual multi-temporal point clouds for each site. As the error of scan geometry here appears minimal, the error of alignment is likely to reflect the relative geometry of marker locations. The nature of peat and other factors including ‘mire-breathing’ can influence the ability to align multi-temporal data (Grayson *et al.* 2012), and largest fluctuations in horizontal and vertical peat surfaces are reported to occur between seasons of the year as a result of water content (Schlotzhauer & Price 1999, Glaser *et al.* 2004). As the errors of alignment determined for all sites here are lower than scan registration errors reported in non-peat soils (11–13 mm; Goodwin *et al.* 2016), this suggests that the phenomenon of mire-breathing was minimal in the sites assessed between May and July 2017.

Terrestrial laser scanning is being used to assess change in a range of morphologically complex environments (Milan *et al*. 2007, Schürch *et al*. 2011, Day *et al*. 2013) and is increasingly being used to provide benchmark data to assess the accuracy of other surveying technologies (Castillo *et al.* 2012, Glendell *et al.* 2017). The resolution of data obtained in this study (in places < 2 mm) and the mean combined error of scanner geometry and registration (1.7 mm at Zalama, 7.6 mm at Ilsos de Zalama and 4.8 mm at Collado de Hornaza) indicate that TLS, particularly with use of fixed reference markers, is an appropriate approach to quantify mm resolution surface change in peatlands. The cost and weight of TLS units have been highlighted as a disadvantage for this approach compared to UAV and ground-based photogrammetry (Glendell *et al.* 2017), and while outright purchase costs of TLS units are in excess of GBP30,000, the FARO X330 can be hired in the UK for less than GBP250 per day. At 5 kg, the FARO is also appropriate for remote field survey, and the combined error reported in this study is lower than the error reported for both UAV and ground-based SfM techniques for mapping erosion specifically in peatlands (Glendell *et al.* 2017). The approach of mesh to cloud (M2C) to quantify surface change was preferred to the option of creating and comparing DEM data (e.g. Grayson *et al.* 2012) as in a DEM each pixel can only have one value of z. In a 3D point cloud it is possible for multiple points to have the same x and y coordinate but different z values. The M2C approach retains the ability to compare change of such complex 3D morphology at fine-scale resolution (Monserrat & Crosetto 2008, Lague *et al.* 2013).

Assessing peatland surface changes in restored and degraded peatlands

The three areas of blanket bog assessed in this study are located within 25 km of each other, oriented in a N–NW aspect and located at an altitude ranging from 1270–1330 m a.s.l. During the period May 2017 to July 2017 all sites also experienced comparable air temperature, rainfall, humidity and wind speeds. As the rate of surface change determined at Zalama was identified to be significantly different to the rate of surface change determined at both Ilsos de Zalama and Collado de Hornaza, this indicates that other factors may be influencing the rate of surface change in exposed peat assessed here. It is worth noting that the rate of surface change determined at Ilsos de Zalama was also identified to be significantly different to the rate of surface change determined at Collado de Hornaza.

The identification of negative mean overall

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surface change for all sites indicates that erosion or peat loss may be the dominant surface process occurring at all sites. It is not surprising that the two highest measurements of erosion/peat loss at Ilsos de Zalama and three highest measurements of erosion/peat loss at Collado de Hornaza were determined in AOI that solely comprise near vertical peat faces. It is, however, of note that some degree of deposition was identified in all AOI at all sites, including those AOI that solely comprise near vertical peat faces. While it is possible that the far higher rates of erosion/peat loss determined at Ilsos de Zalama and Collado de Hornaza compared to Zalama might relate to slumping of peat as a result of fluvial and aeolian erosion processes (Evans & Warburton 2007), trampling by livestock has been suggested to increase natural erosion processes in this region (Heras & Infante 2003). The comparable climatic conditions across the sites during the study, particularly at Zalama and Ilsos de Zalama (located only 500 m apart), support the suggestion of external, anthropogenic influences in addition to natural erosion processes. Both cattle and horses were observed at Ilsos de Zalama and Collado de Hornaza on each survey date in 2017. There are visible striations/incisions resulting from livestock rubbing and scratching heads (horns) in vertical peat faces (Figure 7B), and where livestock trample over the peat there is evidence of disturbance from hooves (Figure 7A). This disturbance from livestock might explain the apparent deposition determined on near vertical exposed peat faces.

The primary difference between Zalama where very low rates of surface change (erosion) were identified and both Ilsos de Zalama and Collado de Hornaza where significantly higher rates of change (peat loss plus erosion) were identified is the restoration intervention and presence of a fence to exclude cattle and horses (Figure 8). The results indicate that while surface change is occurring at Zalama, the presence of livestock is significantly increasing surface change in Ilsos de Zalama and Collado de Hornaza. An additional consequence of installing the fence at Zalama is a stark contrast in the density and diversity of vegetation (Figure 8) and indeed the fenced area may provide the most attractive browse for several kilometres. The fence does not exclude smaller livestock such as sheep and goats, however, and in both May and July 2017, herds of goats were observed to enter the fenced area at Zalama. It is possible therefore, that some of the surface change determined at Zalama is not caused solely by erosion. It is also important to highlight that due to trampling of livestock in unprotected areas, some negative changes determined could be a consequence of peat compaction, although deposition shows clear movement of peat in the areas.

The numbers of livestock in the region of Cantabria has changed significantly over the last century. The stocking density of horses and sheep have remained relatively stable, but the number of goats has doubled, and cattle has increased nine-fold between 1900–2000 (ICANE 2018). This study has only assessed a period of two months (May–July 2017), and reports the first rates of erosion (Zalama) and of peat loss (Ilsos de Zalama and Collado de Hornaza) for three blanket bogs in northern Spain. The erosion determined at Zalama over two months is around a quarter of the annual mean erosion figures for exposed peat in England and Wales (Table 6). However, and of great concern, the rates of peat loss and erosion determined in unprotected blanket bogs

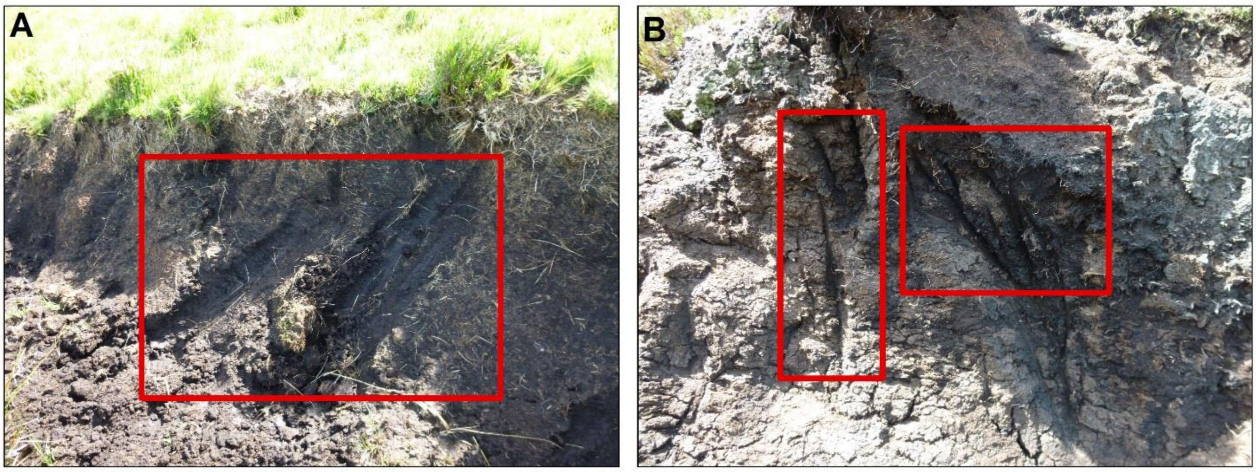

Figure 7. A) Peat disturbance from hooves and B) striations in exposed peat left by livestock horns. Photographs taken by Guaduneth Chico in July 2017.

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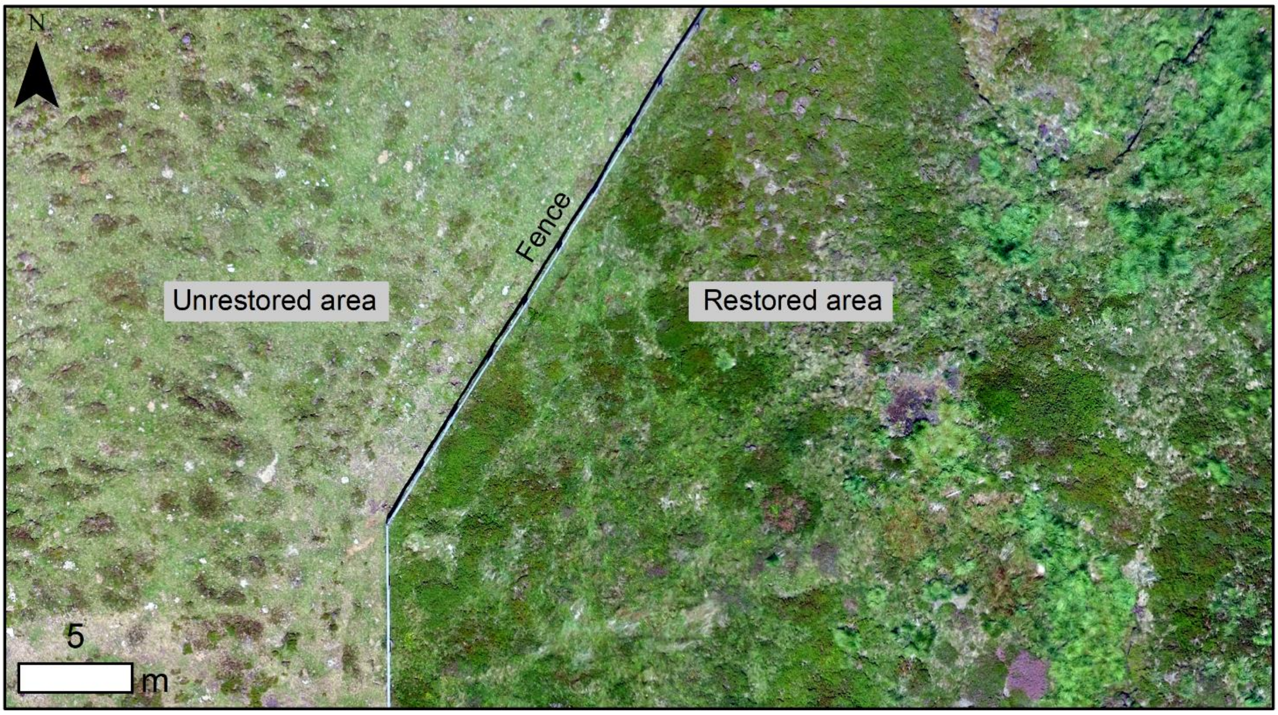

Figure 8. Visual difference in density and diversity of vegetation between restored and unrestored areas at Zalama (imagery captured using SenseFly eBee in July 2017 and processed using Pix4Dmapper).

Table 6. Rates of erosion/peat loss determined over two months for three blanket bogs in north Spain compared to annual rates of peat erosion for England, Wales, Scotland and Tasmania (derived from Evans & Warburton 2007 and Li et al. 2018).

Country	Number of studies	Min (mm)	Max (mm)	Mean (mm)
Annual				
England	18	1.03	73.8	22.4
Wales	3	16	30	23.1
Scotland	2	10	59	36.3
Tasmania	1	-	-	43
Two months (present study)				
Erosion (Zalama)	*3*	*3*	*9.4*	*5.9*
Peat loss (Collado de Hornaza)	*3*	*9.3*	*82.1*	*35.8*

in this study are already equal to the annual rate of peat erosion in England and Wales (Ilsos de Zalama) and equal to the higher mean rates determined in Scotland (Collado de Hornaza; Table 6). It will be important to continue to monitor this surface change over several years, but the method applied here provides rapid indication of the rate of surface change in blanket bogs.

CONCLUSION

This study demonstrates the application of TLS to quantify the rate of surface change in three recently mapped blanket bogs in the Cantabrian Mountains (northern Spain) from May–July 2017. With the use of fixed reference markers, portable TLS units such as the FARO X330 are able to collect mm resolution data and enable determination of surface change with mm level accuracy. The mean rate of erosion determined over two months for the area of exposed peat assessed in this study for the protected blanket bog (Zalama) was quantified at -5.9 mm. However, the mean peat loss/erosion in the areas assessed in the unprotected blanket bogs is 4–6 times greater (-22.9 mm at Ilsos de Zalama; -35.8 mm at Collado de Hornaza) and is already comparable to annual

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rates of erosion determined for exposed peat in the UK. These are the first quantified measurements of peat erosion/loss for Spain and the application of TLS has highlighted a significant impact of livestock on rates of peat loss. Further research is needed to fully understand the spatial variation in erosion and peat loss across blanket bogs in northern Spain, and any seasonal variation resulting from the absence of livestock. The technique can be applied to any peatland and indicates that installation of fences around blanket bog across the Cantabrian Mountains is required imminently to reduce the loss of peat, the associated carbon store and priority habitat.

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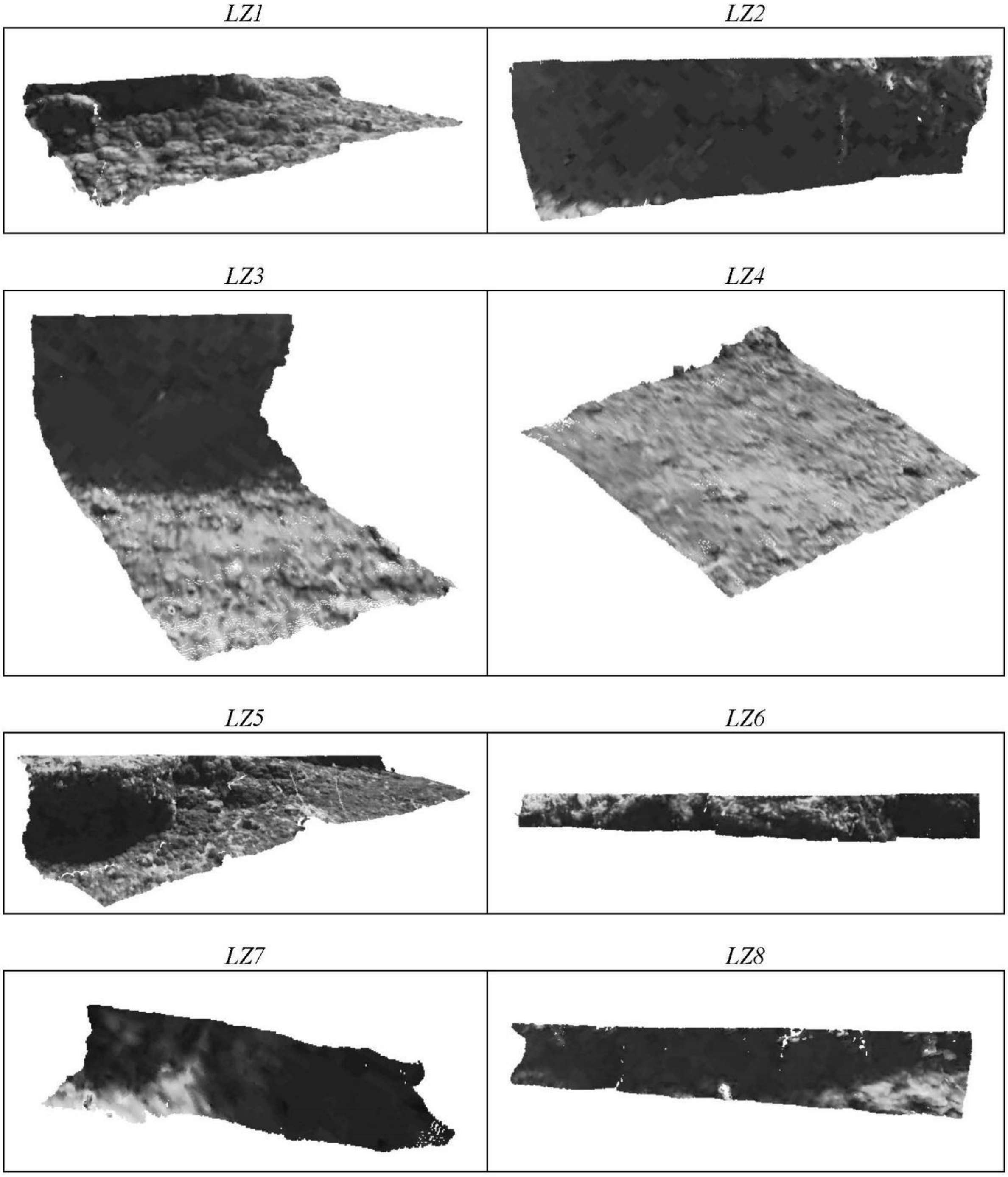
Appendix: Cloud points for the three AOIs.

Zalama



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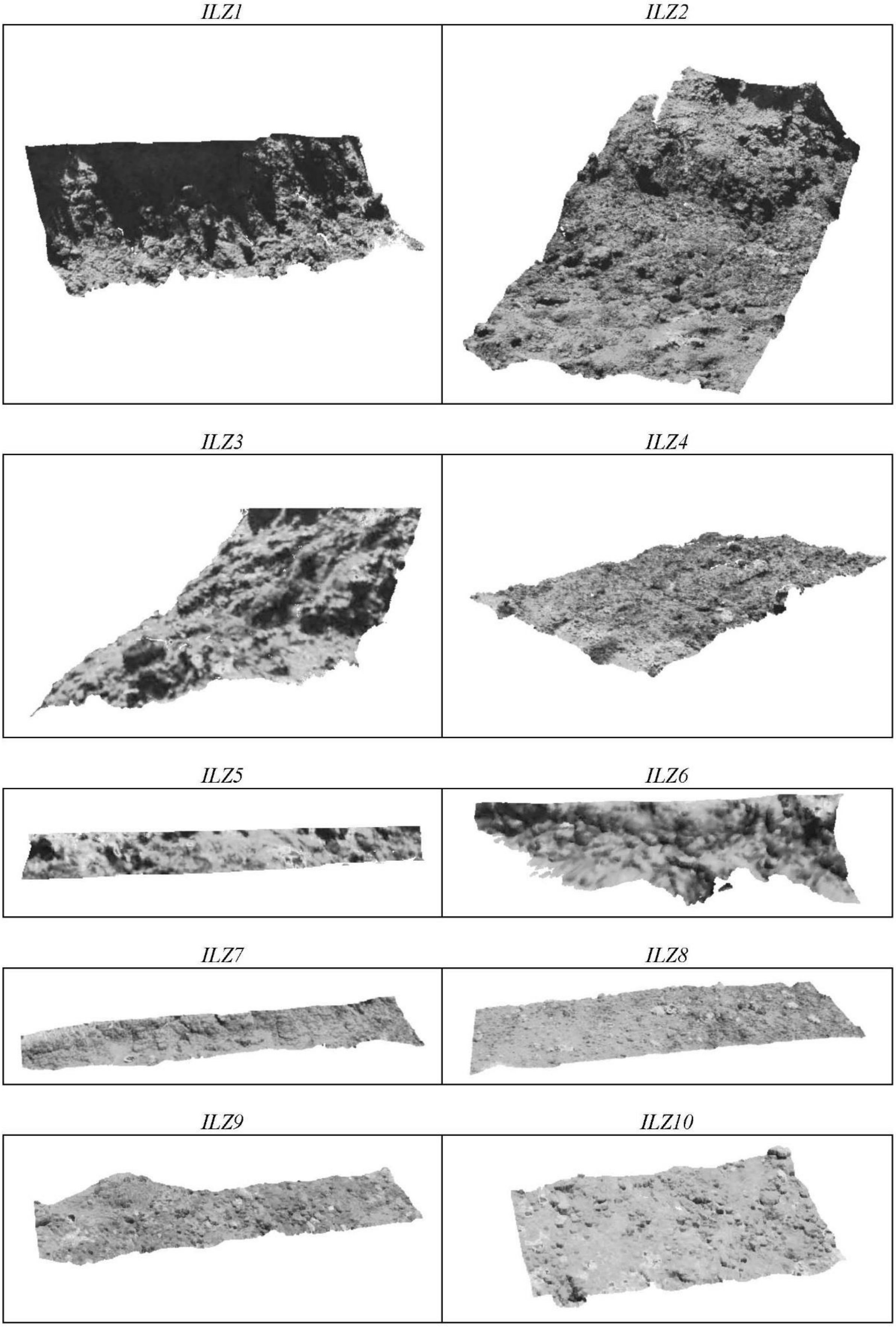
Ilsos de Zalama



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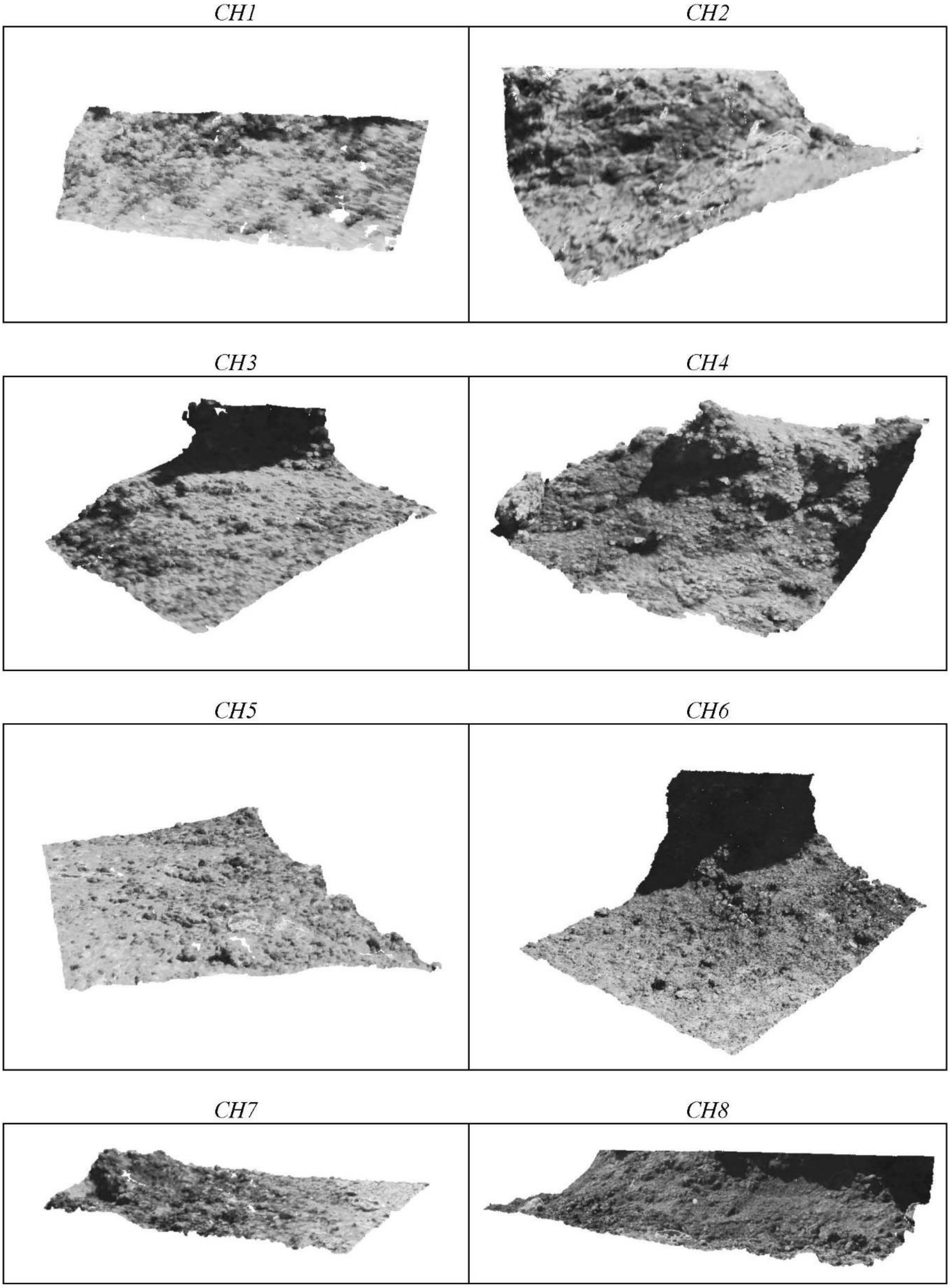
Collado de Hornaza



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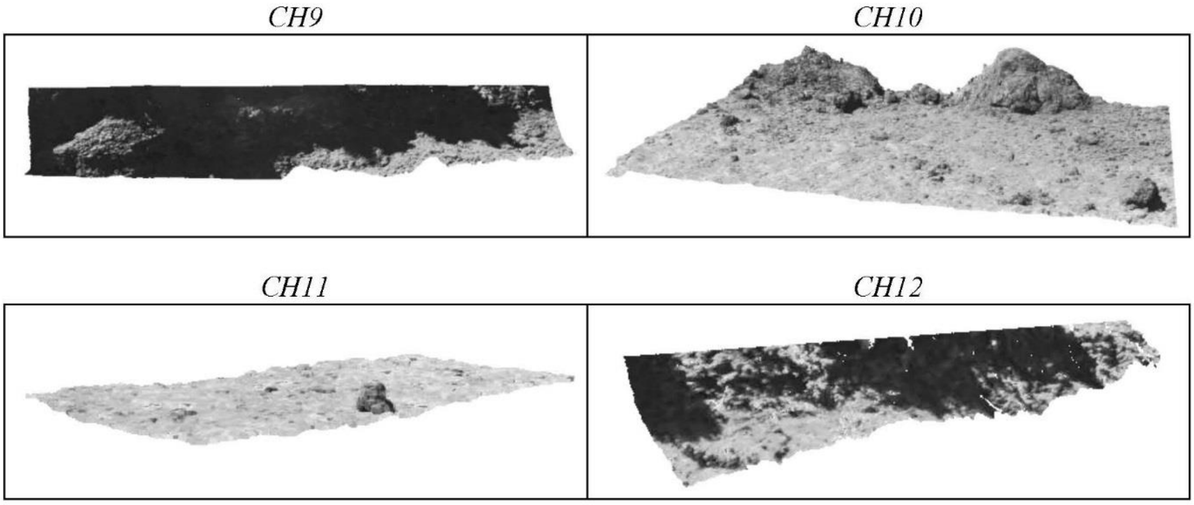

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